

# The Haverford School Gwinn Lecture



## Exploring the Solar System through Space Systems Engineering

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MIT SB '12 SM '14 ScD '17

Haverford '08

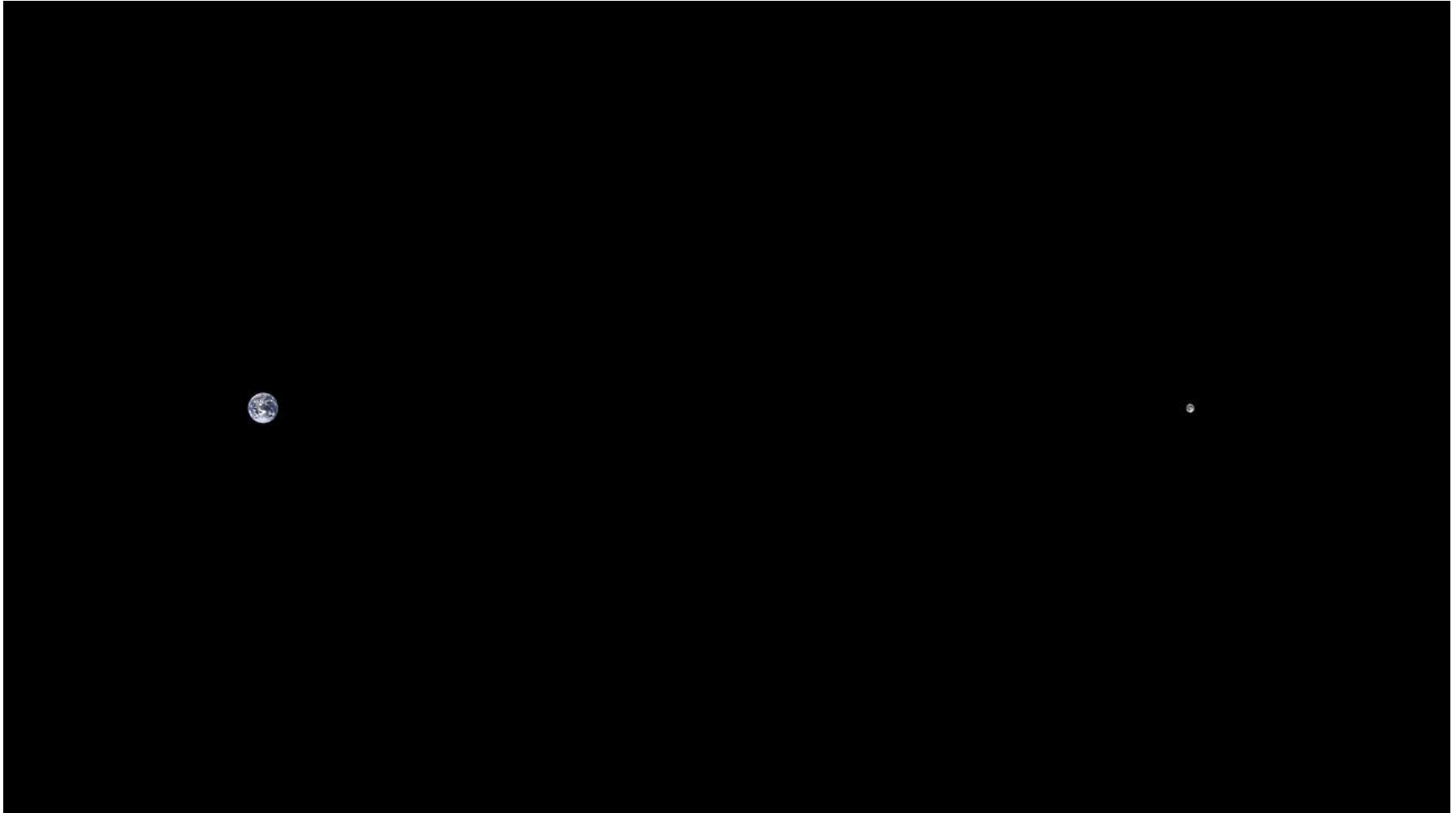
April 13, 2018

# Outline

- Why focus on space?
- From Haverford to MIT
- MIT research highlights
  - Intro to SPHERES
  - Docking ports and Halo structures
  - Snippet of doctoral research
- JPL flight projects
  - Lunar Flashlight
  - MarCO
- Concluding remarks



# Where We've Gone

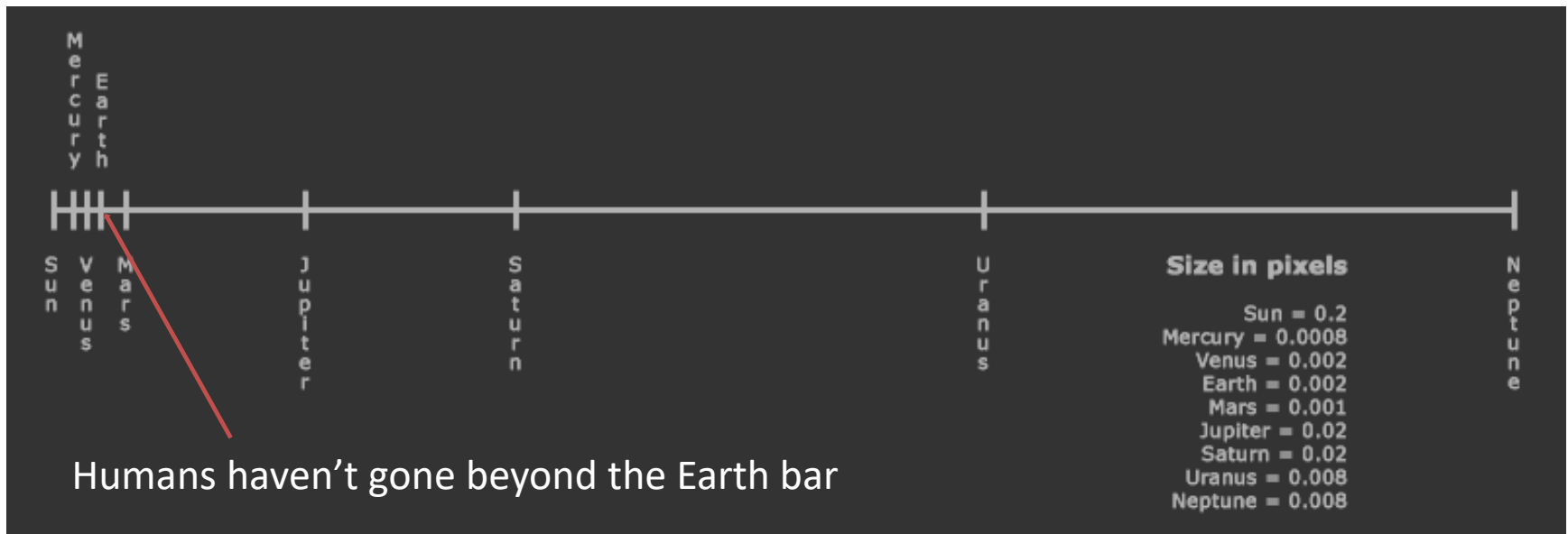


# Where We've Gone

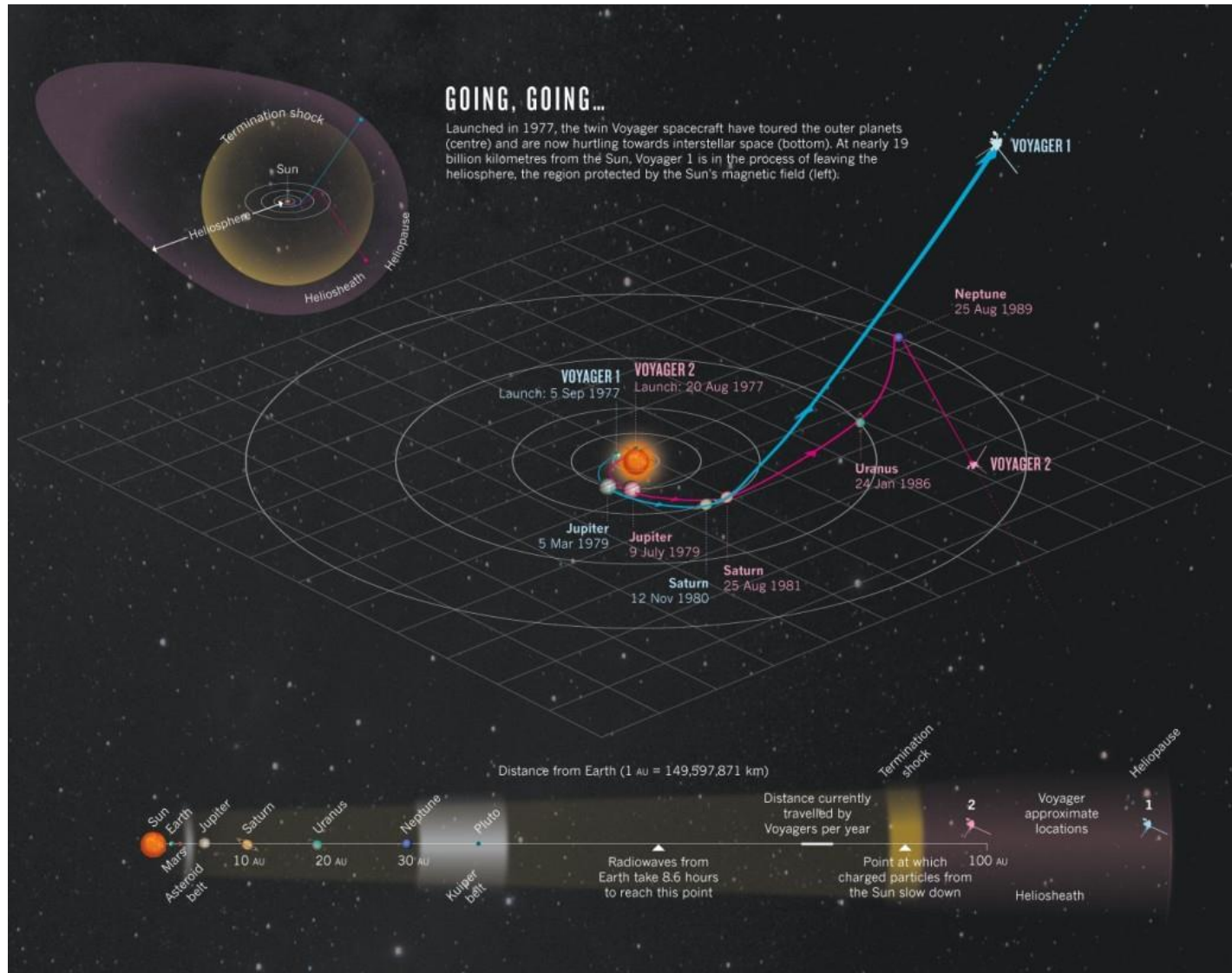




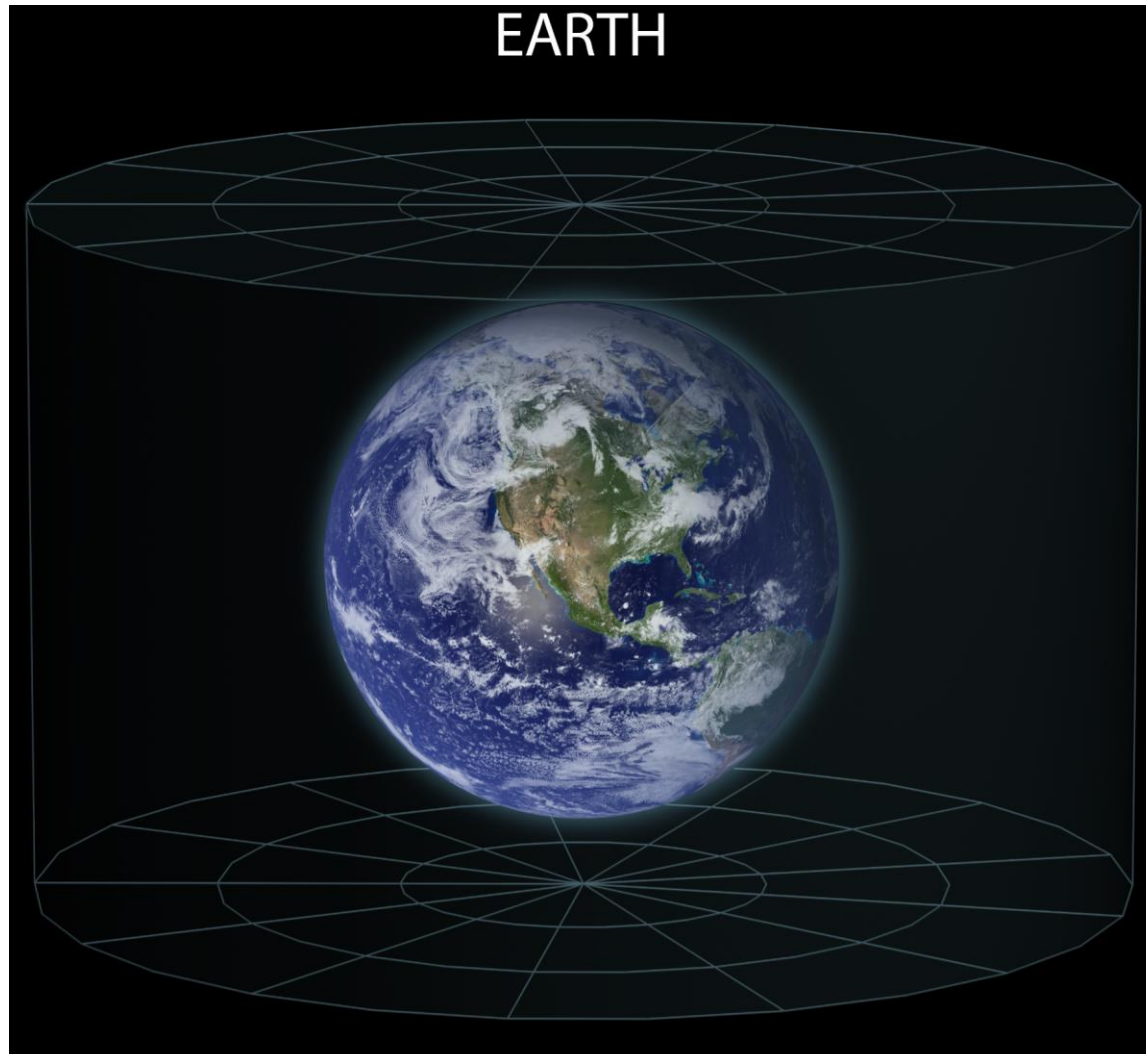
# The Scale of the Solar System



# How Far Humanity Has Reached



# Where We Are

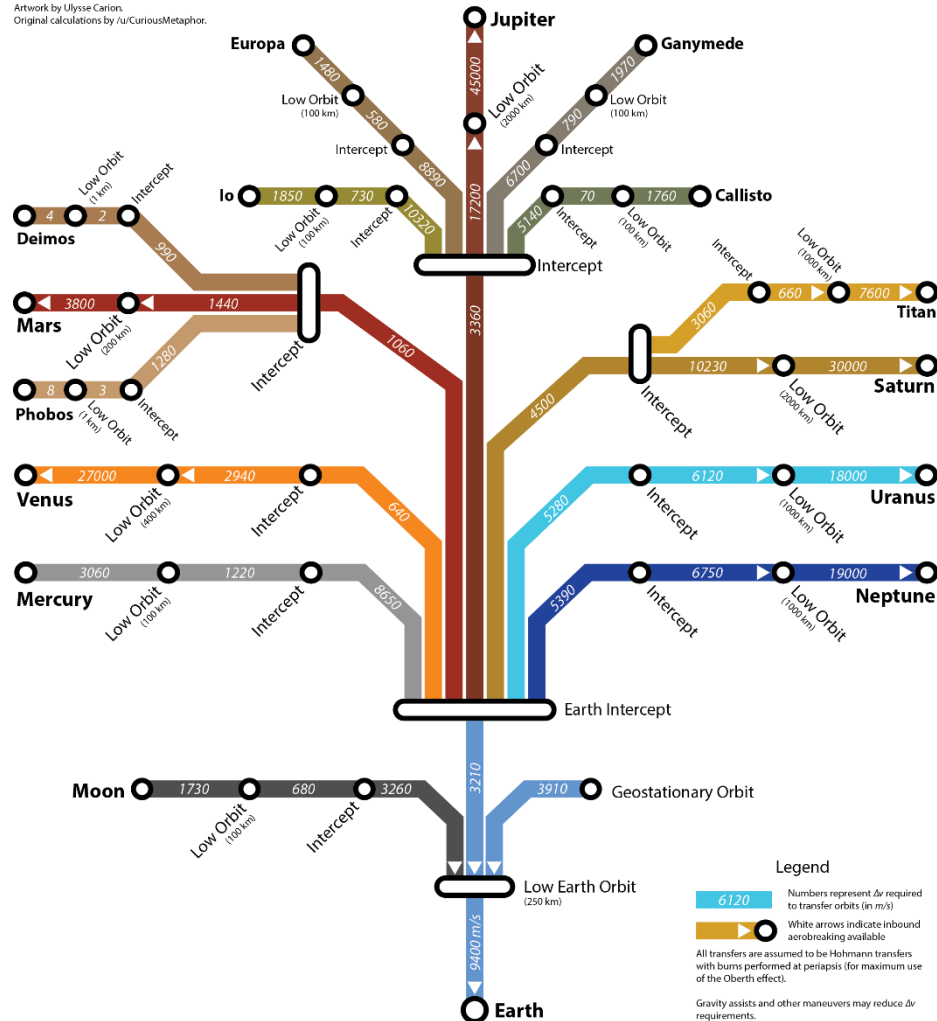


# Getting There is Hard

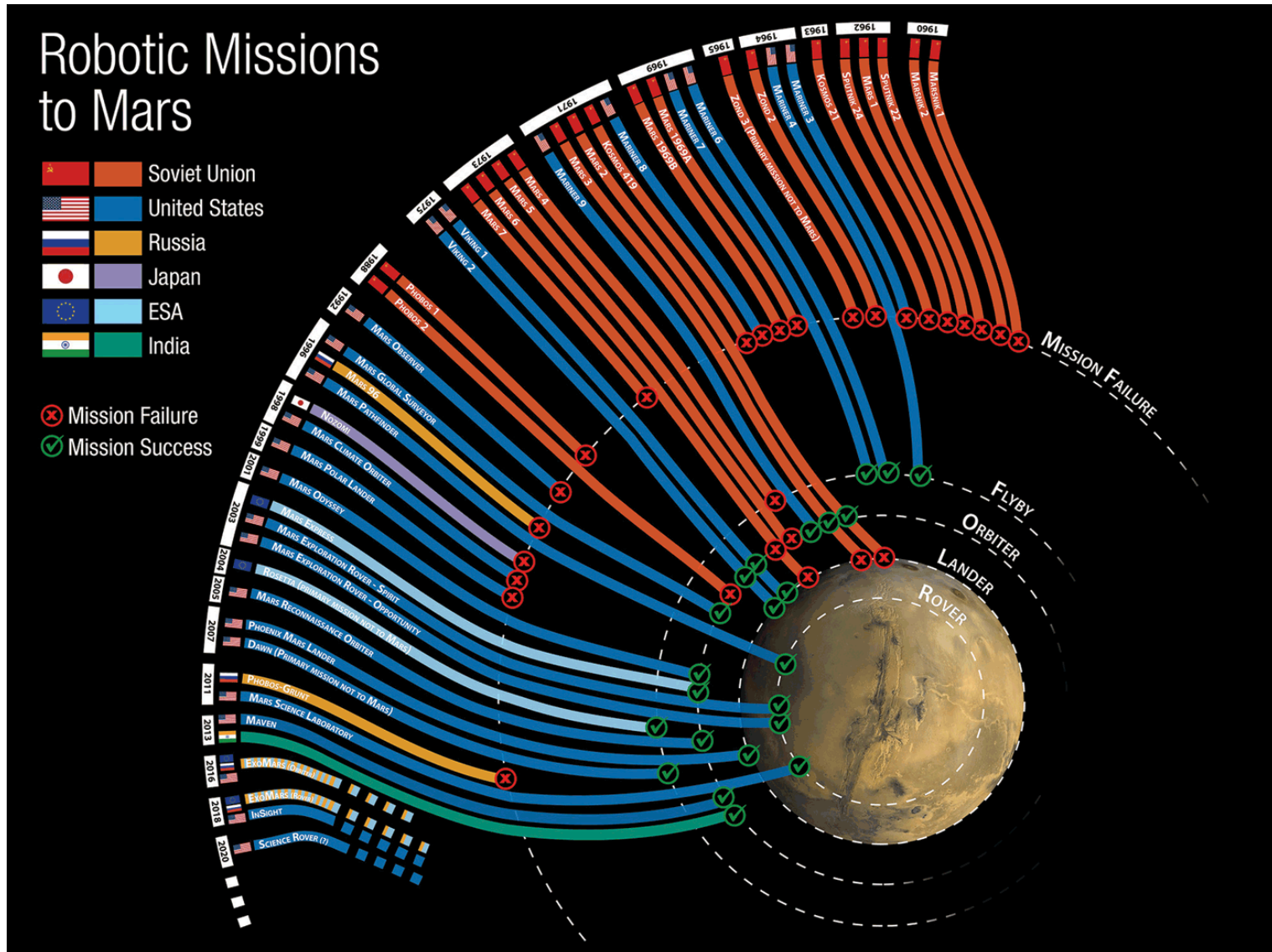
## The Solar System

A subway map

Artwork by Ulysse Carion.  
Original calculations by /u/CuriousMetaphor.



# Getting There is Hard



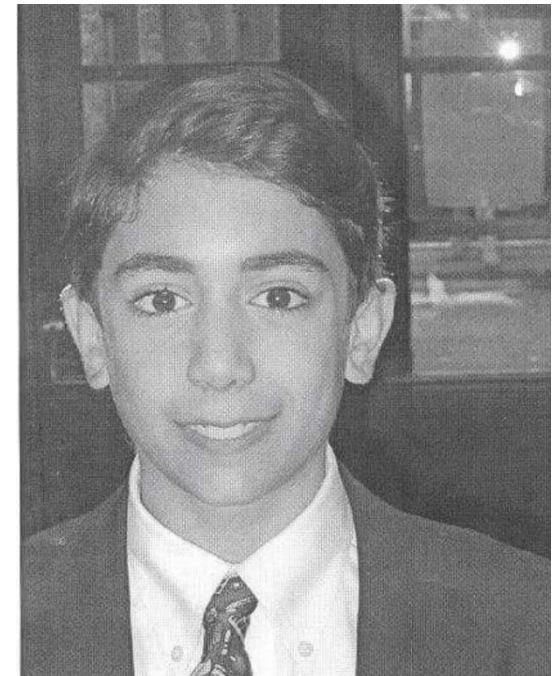
# Getting There is Hard – But Fun!



Working on MarCO in the CubeSat Lab

# Haverford Foundation

- Entered Haverford in 5<sup>th</sup> grade
  - Dr. Turner's science class astronaut reports
- Flying Club 7<sup>th</sup> and 8<sup>th</sup> grade
  - Self-teaching how to fly flight simulators
- Flight instruction
  - First flight at Brandywine airport August, 2003
  - Solo on 16<sup>th</sup> birthday
  - Checkride passed on July 25, 2008
- Tailored classes toward STEM
  - Ms. Cleffi's biology class
  - Ms. O'Brien's physics classes
  - Mr. Maley's electronics class
  - Mr. Rooney's engineering class



Freshman Year

# High School – College Transition

- Creating a new reputation
  - A “reset” on how others perceive you
- Getting used to “low” grades
  - High grades in high school don’t guarantee high grades in college
- Homesickness and feeling isolated
  - Everyone is making the transition together
- Study hall periods can grow to become whole days
  - Time management becomes increasingly crucial



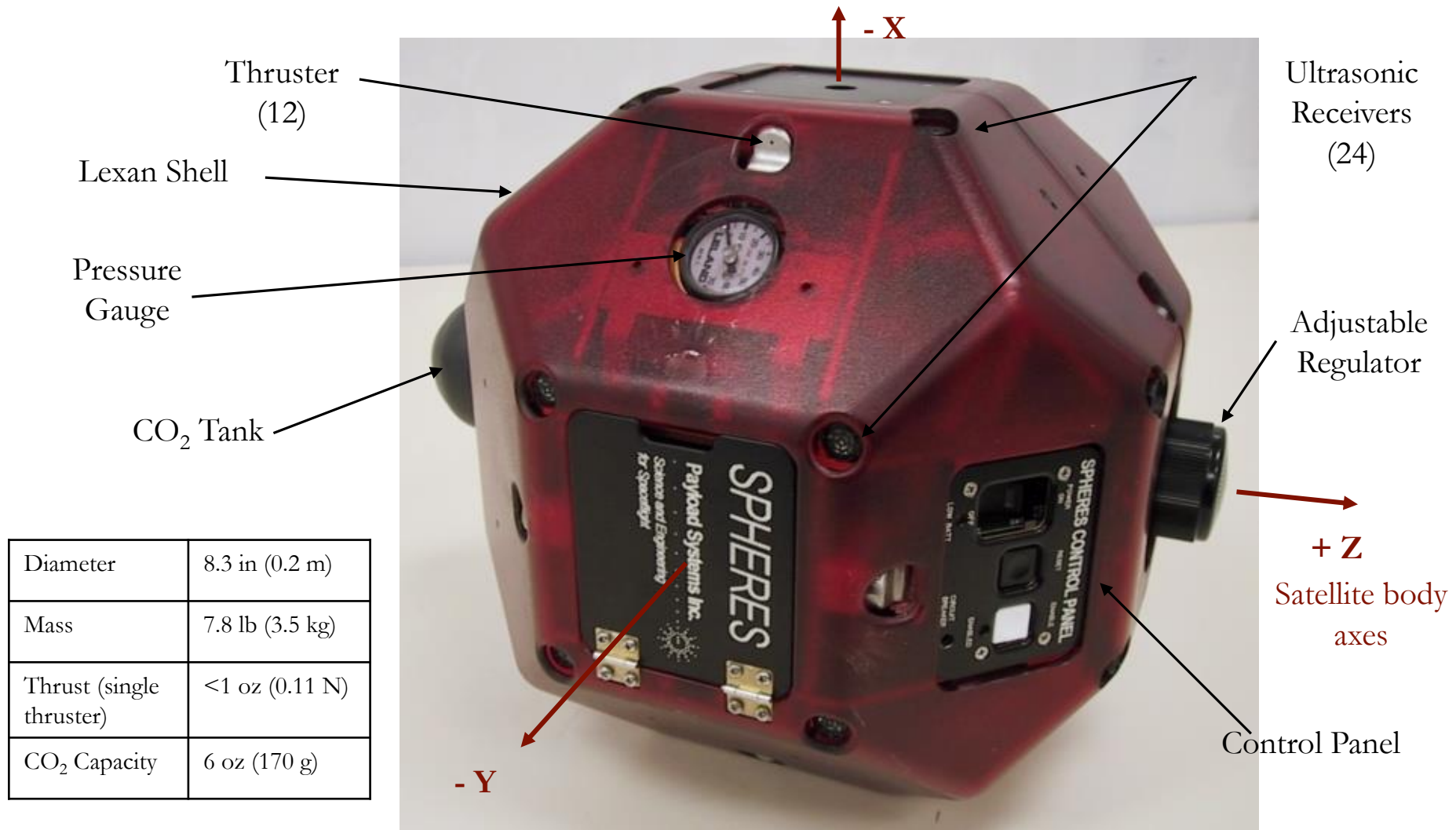
Freshman Year

# SPHERES Motivation

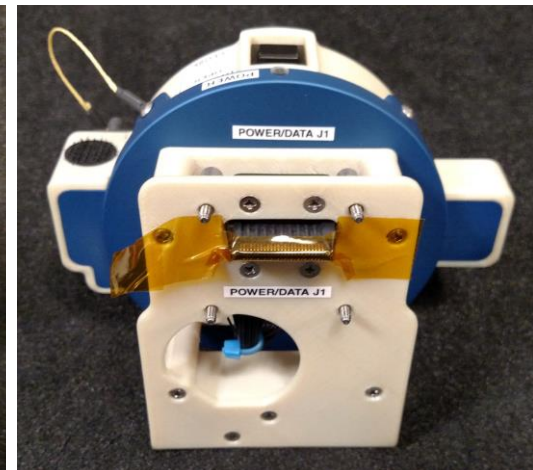
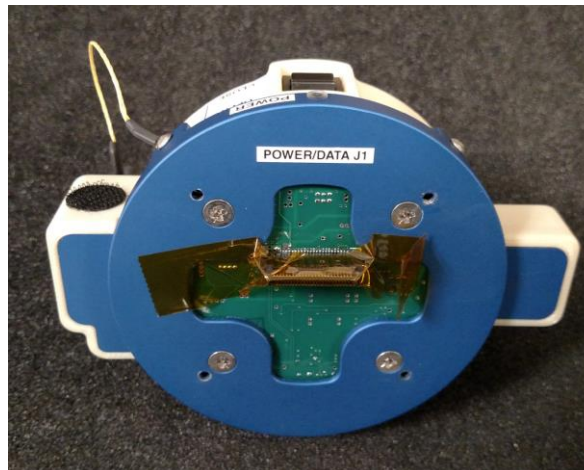
- Develop a **platform** to demonstrate and validate **metrology, control, autonomy, and artificial intelligence algorithms for distributed satellite systems (DSS)**
- Demonstrate different configurations of DSS
  - Rendezvous and docking algorithms
    - Servicing missions
    - Space assembly
  - Autonomous formation flight
    - Optical telescopes (Stellar Imager), space based radar
    - Approved by SERB May 2008: Fractionated Spacecraft (DARPA)
- Provide a **representative environment** for the demonstrations
  - 6 DOF, long duration micro gravity
    - If you can't bring the space environment to the laboratory, take the laboratory into space***



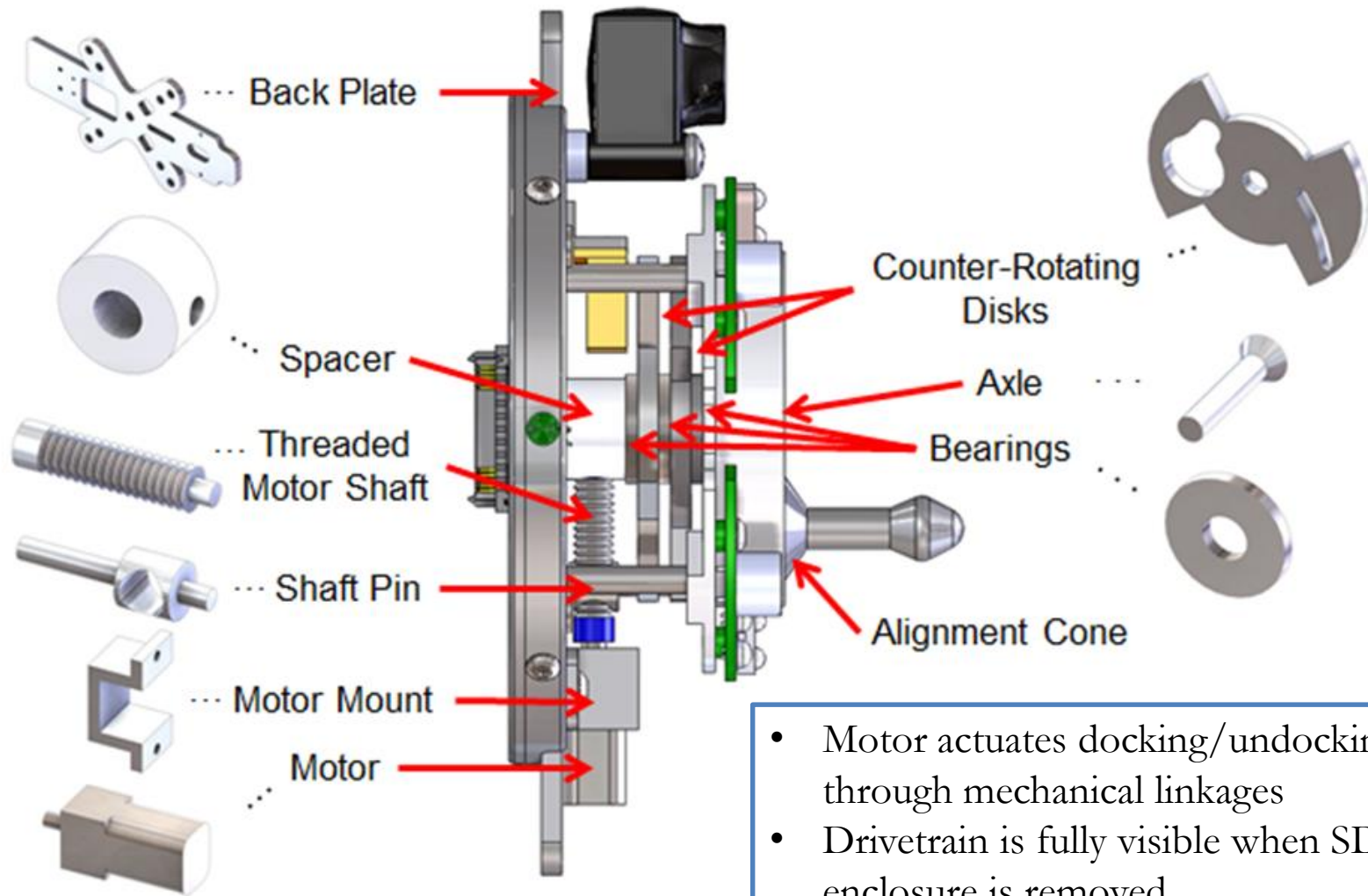
# SPHERES Satellite Overview



# SPHERES Docking Ports

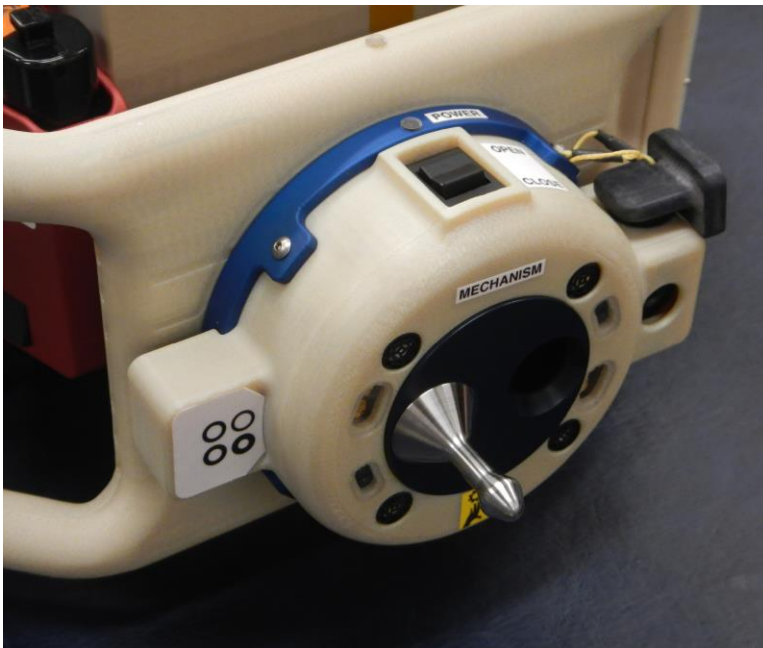


# SDP Drive Train



- Motor actuates docking/undocking through mechanical linkages
- Drivetrain is fully visible when SDP enclosure is removed

# Attachment to Satellites

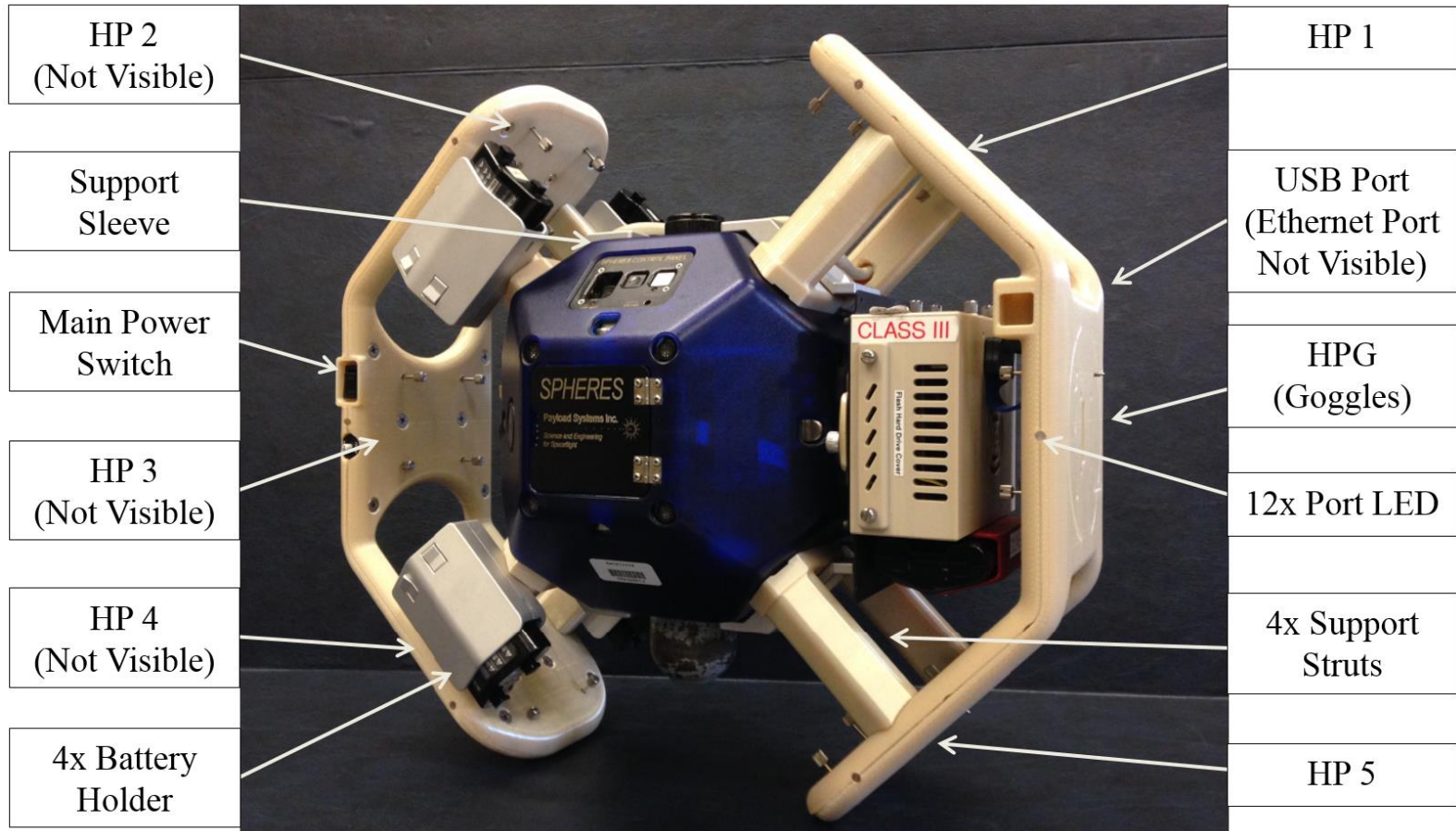


Directly to SPHERES Halo



Via Standoff to SPHERES Satellite

# Halo System Overview



# Reduced Gravity Testing

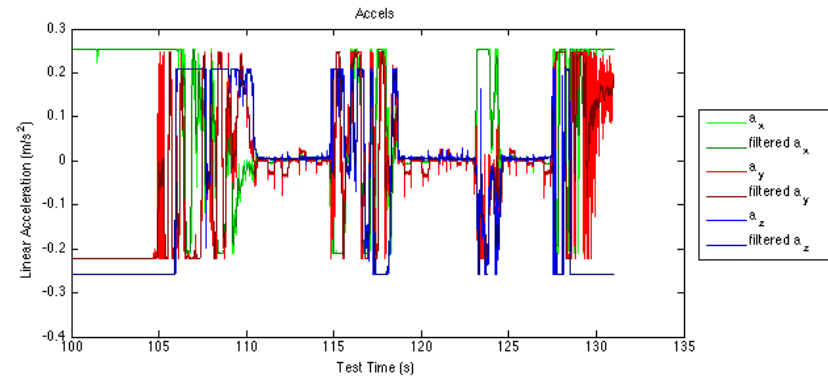


## Science Accomplished

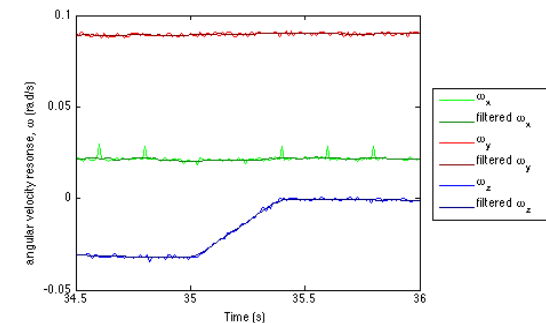
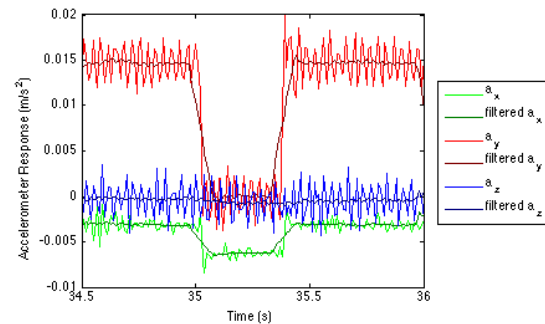
- Inertial ID multiple hardware configurations
- Plume impingement characterization of the Halo structure
- Global metrology performance with a Halo in 6DOF
- Docking repeatability and Controllability of several aggregated systems

# Sample RGA Thruster Pulse Analysis

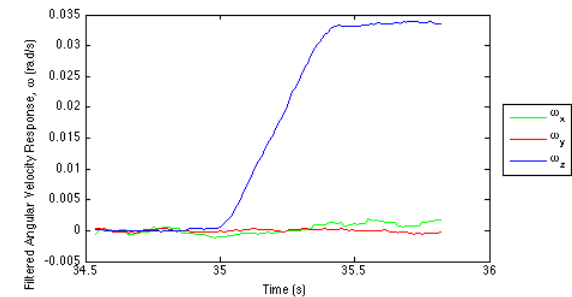
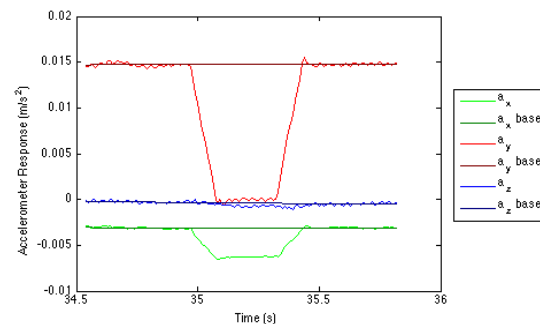
Accelerometer response through a single parabola



Raw accelerometer and gyro data of a thruster pulse with a moving average filter



Final acceleration and angular velocity response to thruster pulse

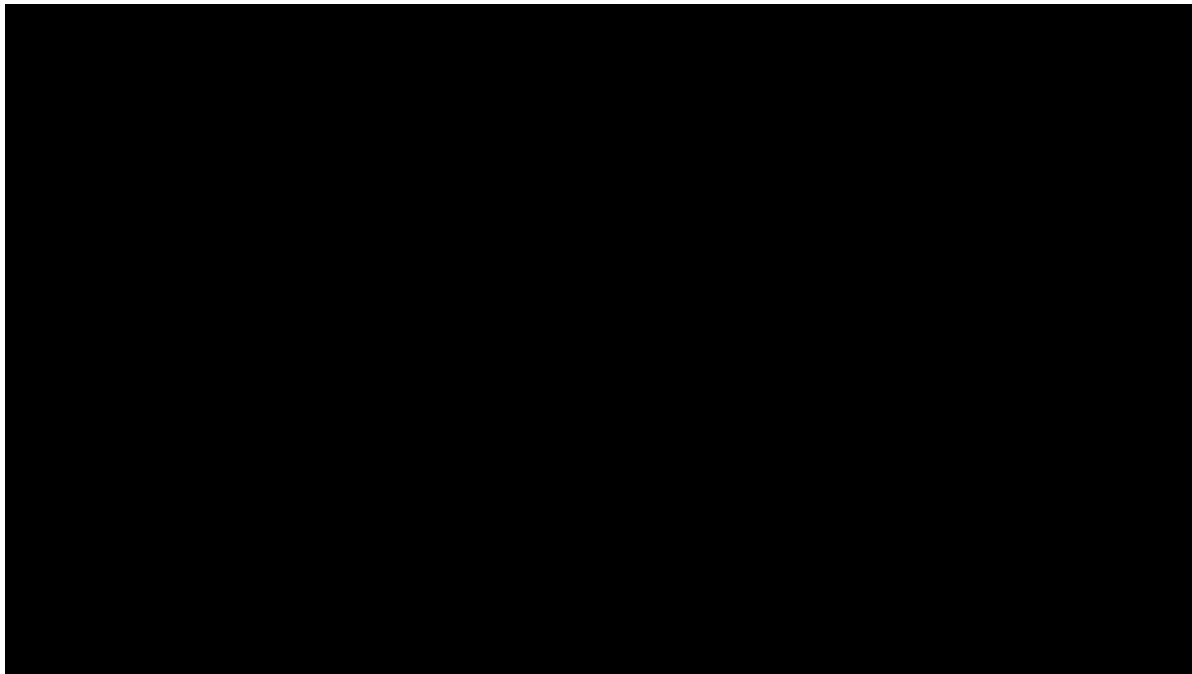




# Accomplishments of TS078: SDP Checkout



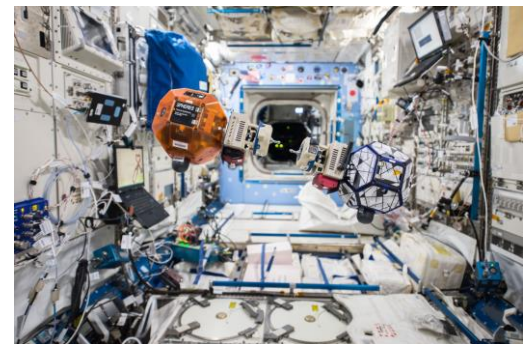
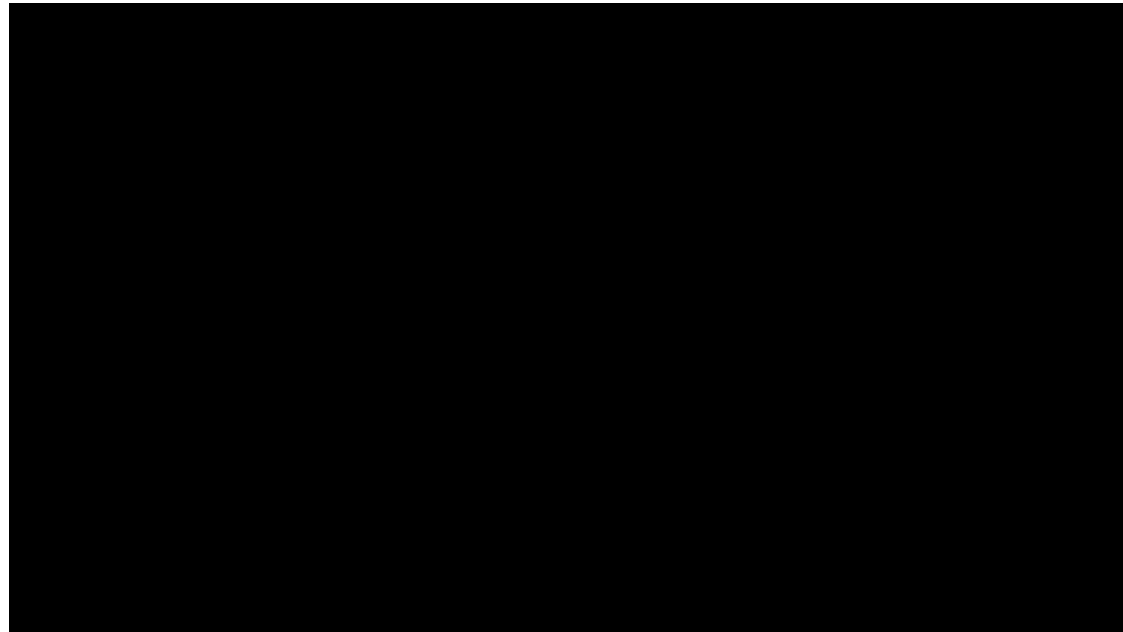
- Docked **calibration** and hardware **checkout**
- **Mass ID** of newly integrated systems
- **Global metrology-only docking attempt**
- **Camera and metrology docking attempt** to integrate the new sensor during approach
- Demonstration of **reconfigurable controller** for both translational and rotational maneuvers



# Accomplishments of TS081: SDP Science 1



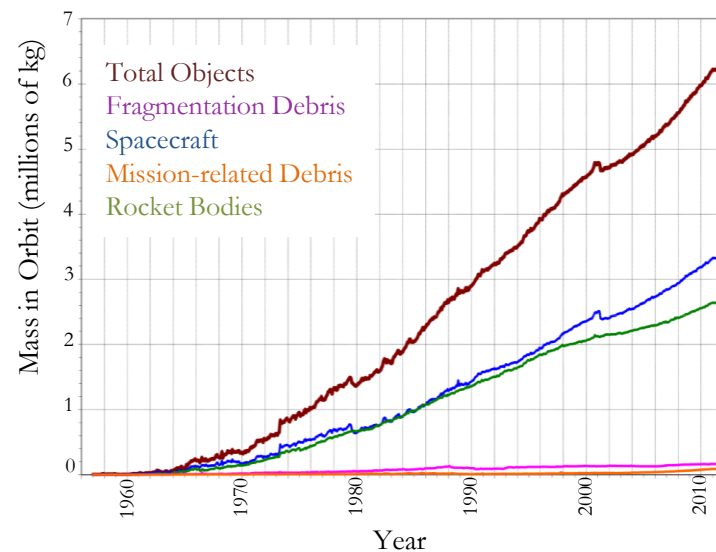
- Record a satellite tumbling about its intermediate axis in 6DOF microgravity for educational use and development of new computer vision tracking algorithms
- Demonstrate **improved reconfigurable controller** during docked translation and rotation maneuvers
- Demonstrate **repeatable docking approaches** using both global metrology and the docking port camera



# Motivation: Mission Applications

- Future missions requiring soft docking with potentially tumbling Targets
  - Spacecraft Servicing [Guo, Wang, Reintsema, Fredrickson, Horsham]
  - Spacecraft Assembly [Barnhart, Guo, Chu, Stroupe]
  - Active Debris Removal (ADR) [Lampariello, Hillenbrand, JSC, Reintsema]
- Goal:** Soft docking with uncooperative, naturally tumbling, rigid bodies with uncertain properties
  - Study ADR of rocket bodies because of extensibility to other missions

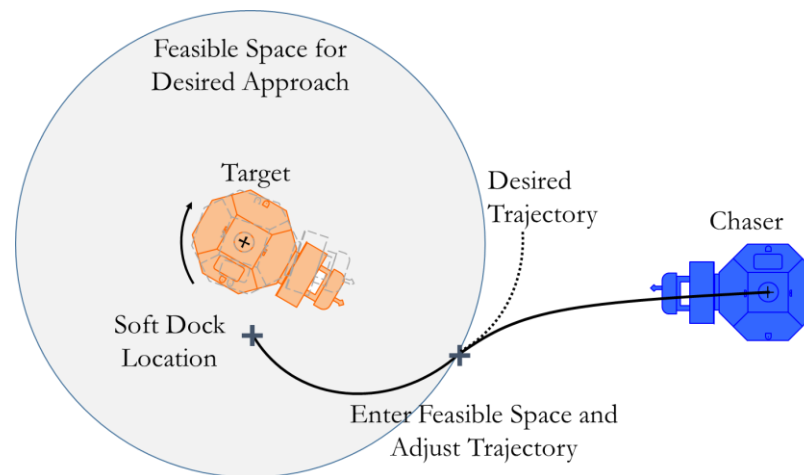
	Target	Servicing	Assembly	ADR
Technical	Uncooperative	✓		✓
	Tumbling	✓		✓
	Flexible	✓	✓	
	Need Multiple Dockings		✓	
	Need Soft Dockings	✓	✓	✓
	Uncertain Properties	✓		✓
Operational	Threat to Others/Urgency			✓
	Currently Orbiting	✓		✓



<http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNV16i2.pdf>

# Problem Statement

- Scenario:
  - A rigid, uncooperative, on-orbit target is observed to be tumbling
  - Want to deorbit the target with autonomous chaser satellite
  - Risk of damaging chaser and generating more debris
- Objective:
  - Improve design of chaser for soft docking to target object with uncertain properties
  - Reduce the risks through the use of 1g testing to help validate 0g simulations



# Challenges Faced in ADR Scenario

**Goal:** Soft docking with uncooperative, naturally tumbling, rigid bodies with uncertain properties

- Urgency requires computational efficiency
- Minimize fuel consumption
- Target properties are initially uncertain  
[Riesing, Gottlieb, Vallado, Titov, Schueller, Simon]
- Adhere to constraints (e.g. contact velocity and Chaser acceleration)  
[Steigler]
- Coupled translations and rotations  
[Hess, Evans]

Trajectory  
Generation

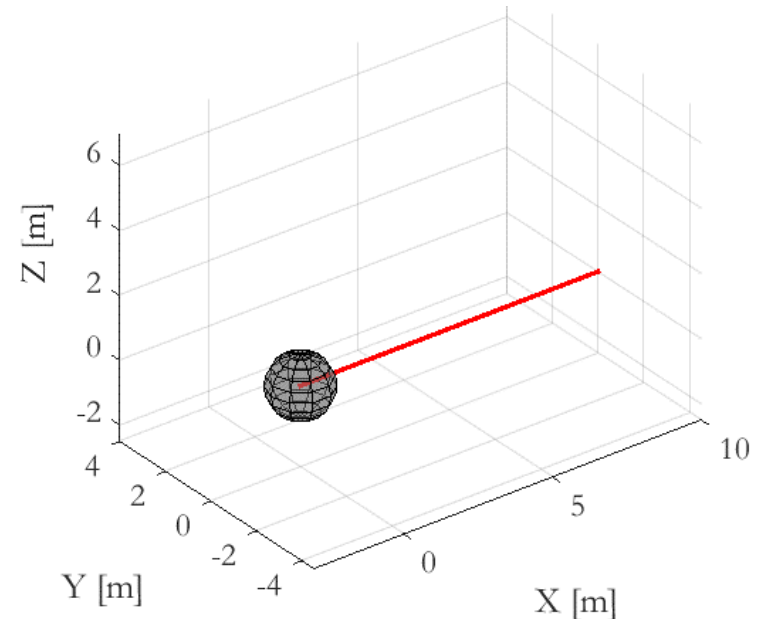
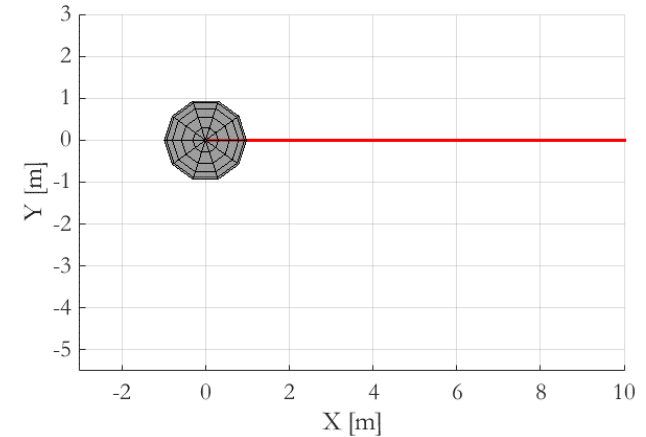
Chaser/Target  
Matching

Simulation  
Validation

# Key Definitions

- “Docking” refers to docking, capture, or berthing
  - Occur quickly compared to orbital period
- “Target” refers to a rocket body requiring soft contact docking
- “Chaser” refers to an ADR satellite capable of thrusting in any direction
- “Synchronous” refers to approaching along the Target’s docking axis to maintain Target lock

**SDTT: Synchronous Docking  
to a Tumbling Target**

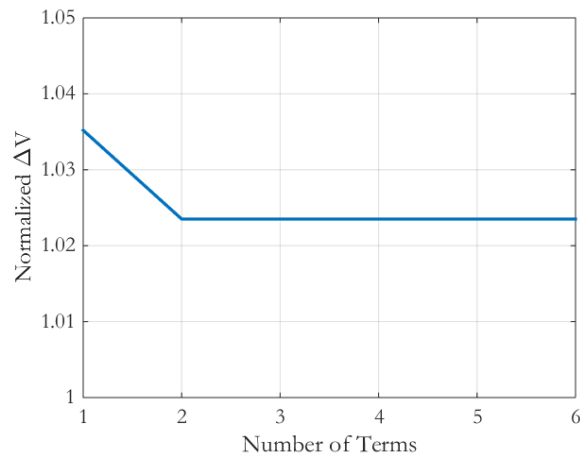


# Efficient Parameterization of a Trajectory

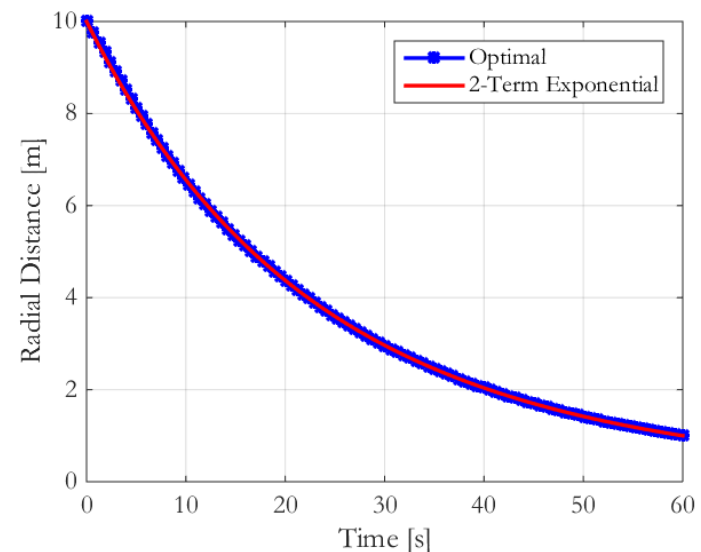
Thesis Contribution: Identified that a reduced parameterization of the optimal trajectory exists to enable rapid optimization

- Specify  $P = [t_f, r_0, r_f, J, \omega]$  properties for various tumbles
- Consider  $\Delta V$  expenditure for translation
- Parameterized the optimal trajectory using four parameters  

$$r(t) = b_1 e^{-c_1 t} + b_2 e^{-c_2 t}$$



Example: flat spin  $P = [t_f = 60s, r_0 = 10m, r_f = 1m, J = [1 \ 1 \ 1], \omega = [0 \ 0 \ 5]deg/s]$



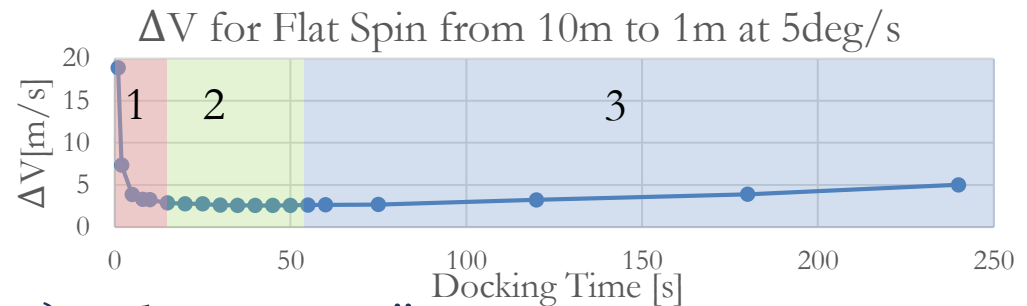
Example	Optimal	2-Term Exponential
$\Delta V$ Percent	100	102
Computation Time Percent	100	23



# How Acceleration Terms Interact to Create Minimum $\Delta V$ Trajectory

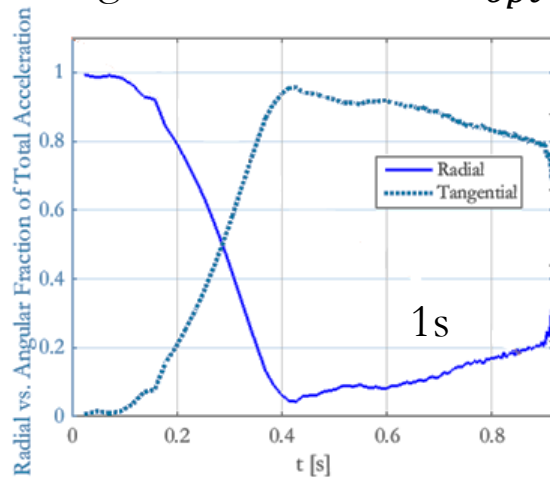


- Varying  $t_f$  enables identification of operation regimes based on acceleration terms near fuel minimum

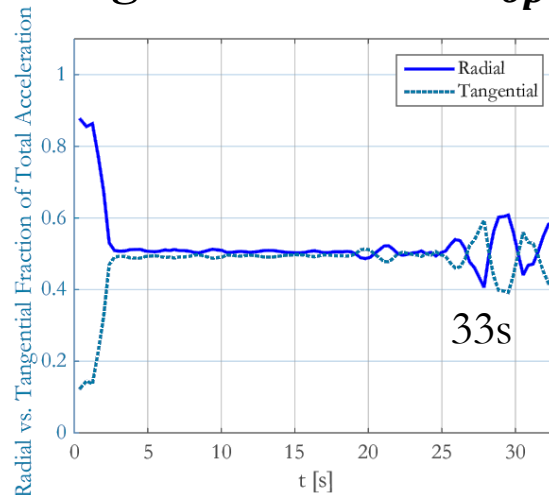


- Radial:  $a_{centripetal} = \omega \times (\omega \times r)$  and  $a_{linear} = \ddot{r}$
- Tangential:  $a_{Coriolis} = 2\omega \times \dot{r}$  and  $a_{angular} = \dot{\omega} \times r$

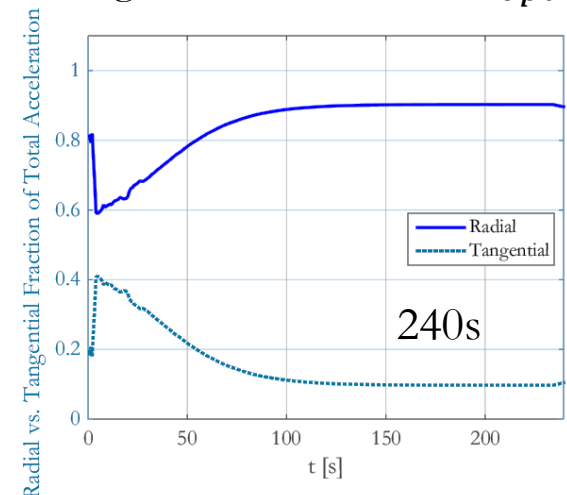
Regime 1:  $\Delta V = 7.8\Delta V_{opt}$



Regime 2:  $\Delta V = \Delta V_{opt}$



Regime 3:  $\Delta V = 2.9\Delta V_{opt}$

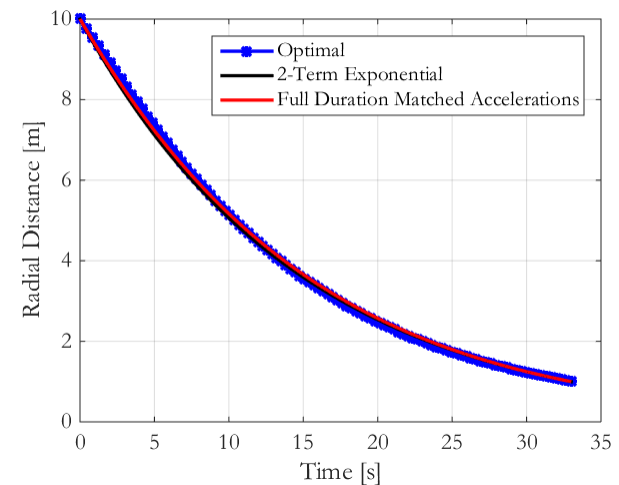


Thesis Contribution: Found that minimum fuel trajectories match tangential and radial acceleration

# Trajectory Generation from Flat Spin Differential Equation

Flat spin matched acceleration case requires only two parameters to be found using boundary conditions

- Flat spin with constant spin rate:
  - $2\omega\dot{r} + \dot{\omega}r = \omega^2r + \ddot{r}$
  - General solution  $r(t) = c_1e^{\omega t} + c_2te^{\omega t}$
- Boundary conditions to solve for parameters
  - $(r_0, t_0), (r_f, t_f) \rightarrow \begin{bmatrix} e^{\omega t_0} & t_0e^{\omega t_0} \\ e^{\omega t_f} & t_fe^{\omega t_f} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} r_0 \\ r_f \end{bmatrix}$
- Flat spin trajectory generation reduces computation cost to solving for two constants without optimization or propagation



	Optimal	2-Term Exponential	Matched Acceleration
$\Delta V$	2.247m/s	2.262m/s	2.248m/s
Computation Time Percent	100	25	0.02

# Differential Equation to Find Optimal Trajectory

- Generic tumble case:

- Define state  $x = \begin{bmatrix} r \\ \dot{r} \end{bmatrix}$

- Then:  $\dot{x} = \begin{bmatrix} 0_{3 \times 3} & I_{3 \times 3} \\ C_{3 \times 3} & B_{3 \times 3} \end{bmatrix} x = A(t)x$  (LTV), with

$$B_{3 \times 3} = 2 \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}$$

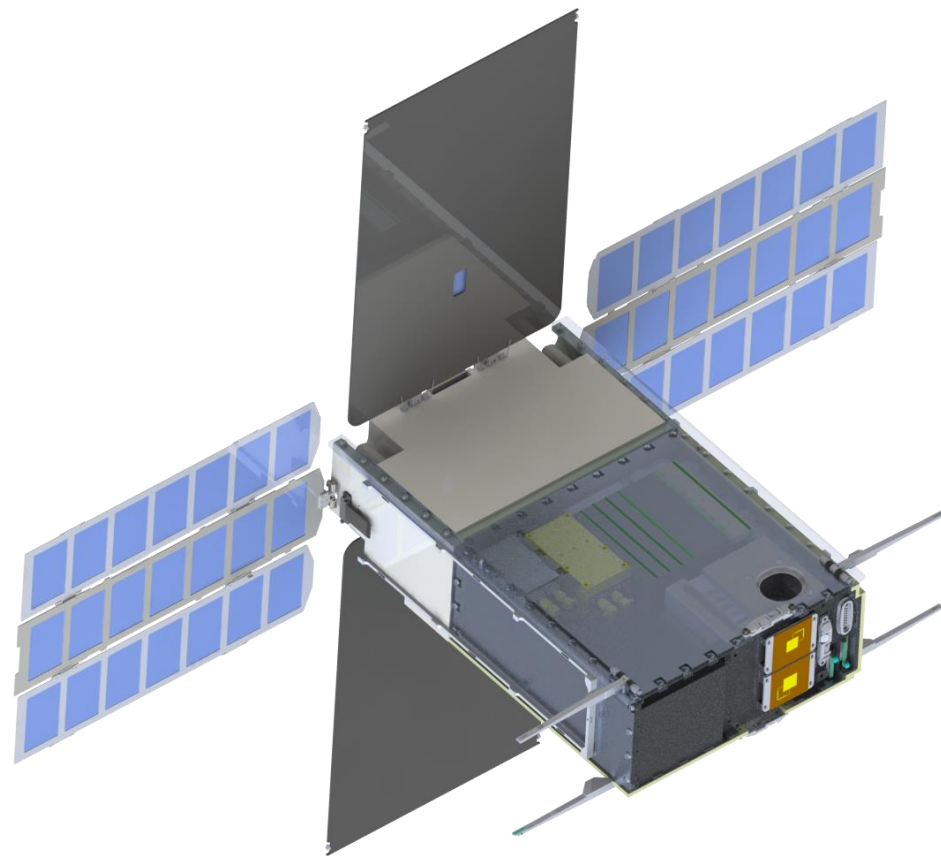
$$C_{3 \times 3} = \begin{bmatrix} \omega_2^2 + \omega_3^2 & -\dot{\omega}_3 - \omega_1 \omega_2 & \dot{\omega}_2 - \omega_1 \omega_3 \\ \dot{\omega}_3 - \omega_1 \omega_2 & \omega_1^2 + \omega_3^2 & -\dot{\omega}_1 - \omega_2 \omega_3 \\ -\dot{\omega}_2 - \omega_1 \omega_3 & \dot{\omega}_1 - \omega_2 \omega_3 & \omega_2^2 + \omega_1^2 \end{bmatrix}$$

Time dependence  
requires numerical  
propagation

- Boundary conditions specified for forward or backward propagation as piecewise LTI system
  - $\dot{r}_0, r_0, r_f$  for forward propagation
  - $\dot{r}_f, r_0, r_f$  for backward propagation

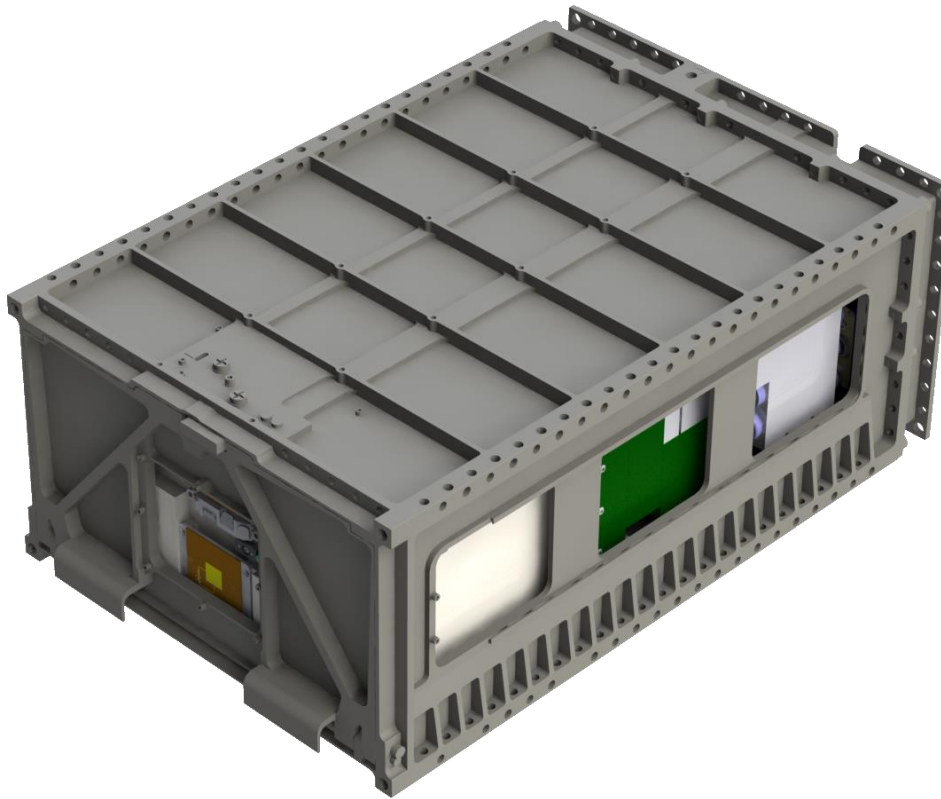
Each propagation of the LTV system takes 0.05% the time of the full optimization

# Lunar Flashlight Mission

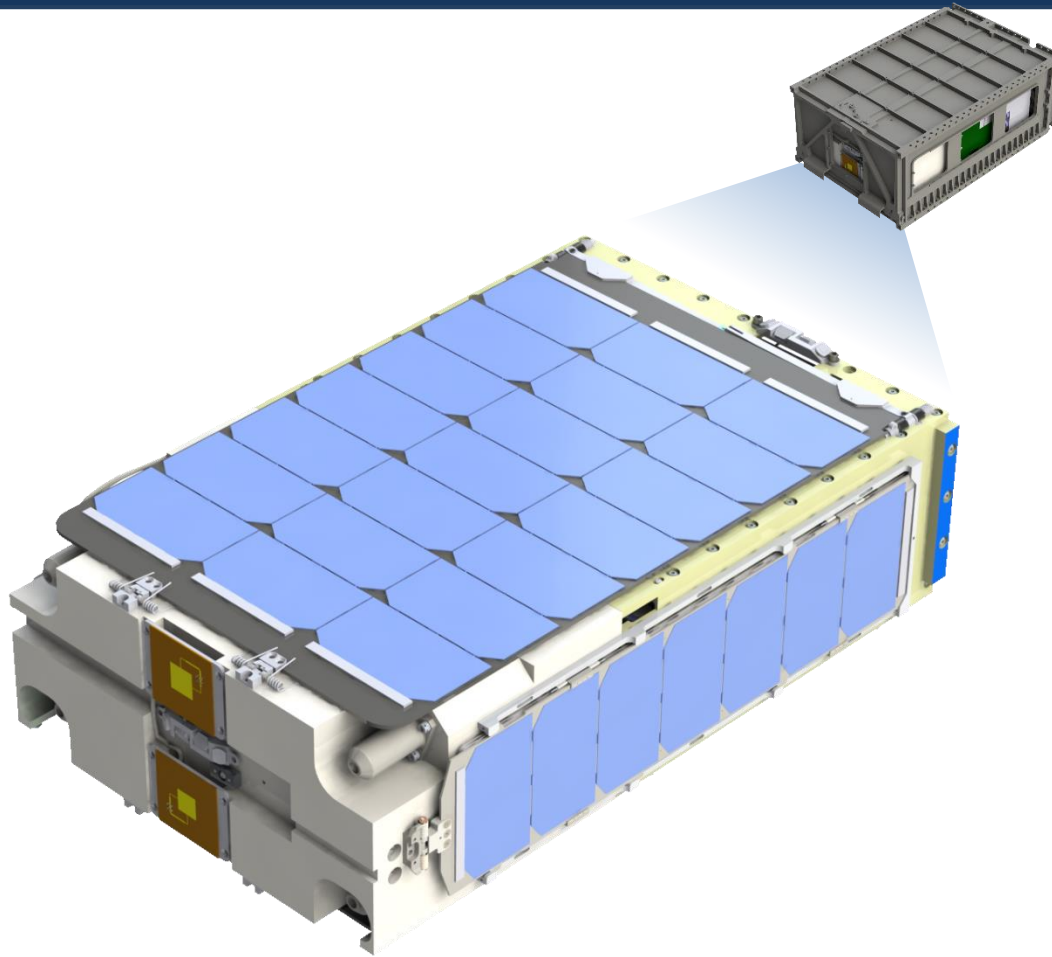


- Lunar Flashlight spacecraft
  - 6U CubeSat
  - Launching as secondary payload on SLS EM-1
  - Approximately 8 month mission, final 2 months are lunar science orbits
  - Payload consists of laser diode and onboard spectrometer to measuring reflected light
- Collaboration between JPL and Marshall Spaceflight Center (Propulsion, Science)

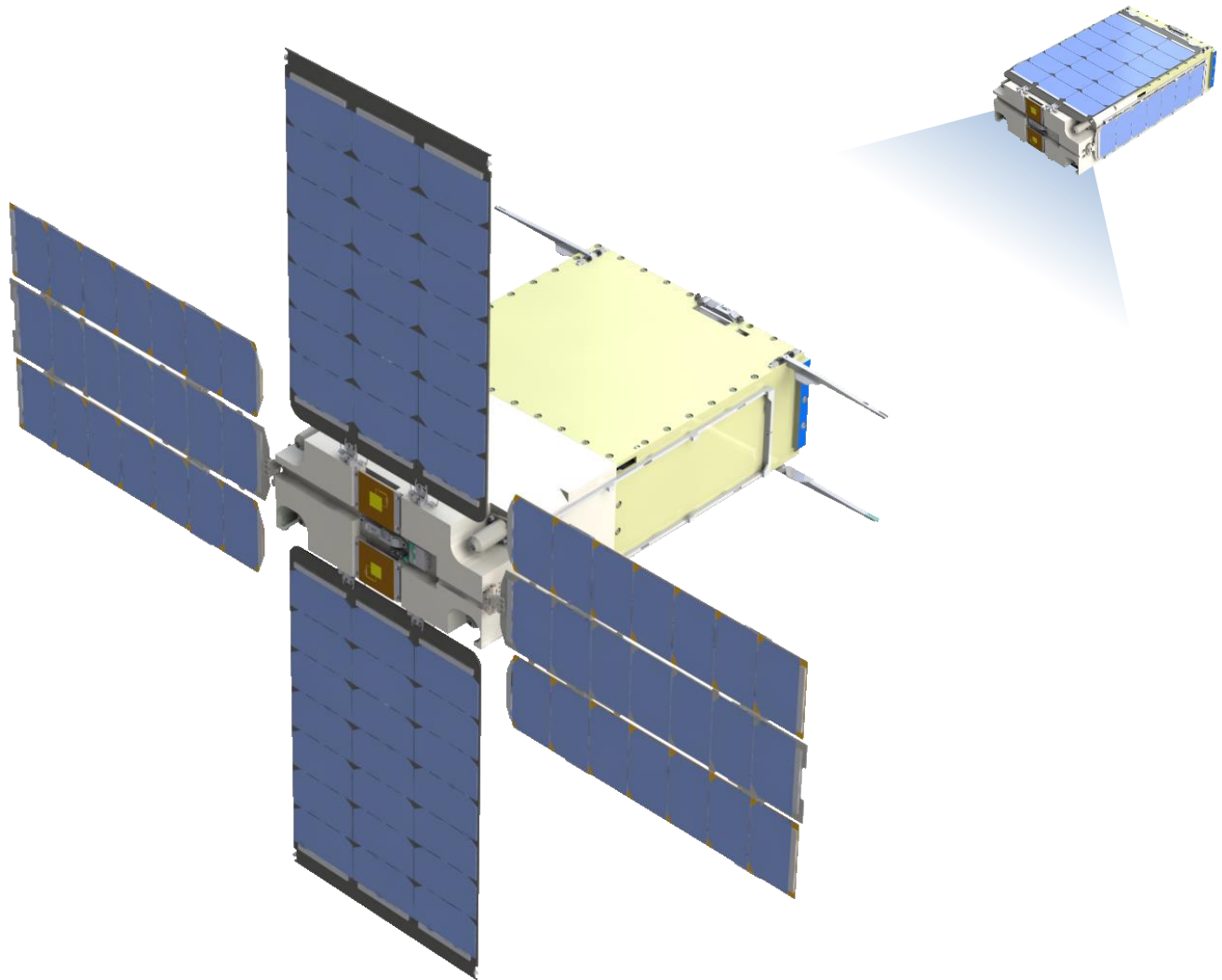
# Lunar Flashlight within Deployer



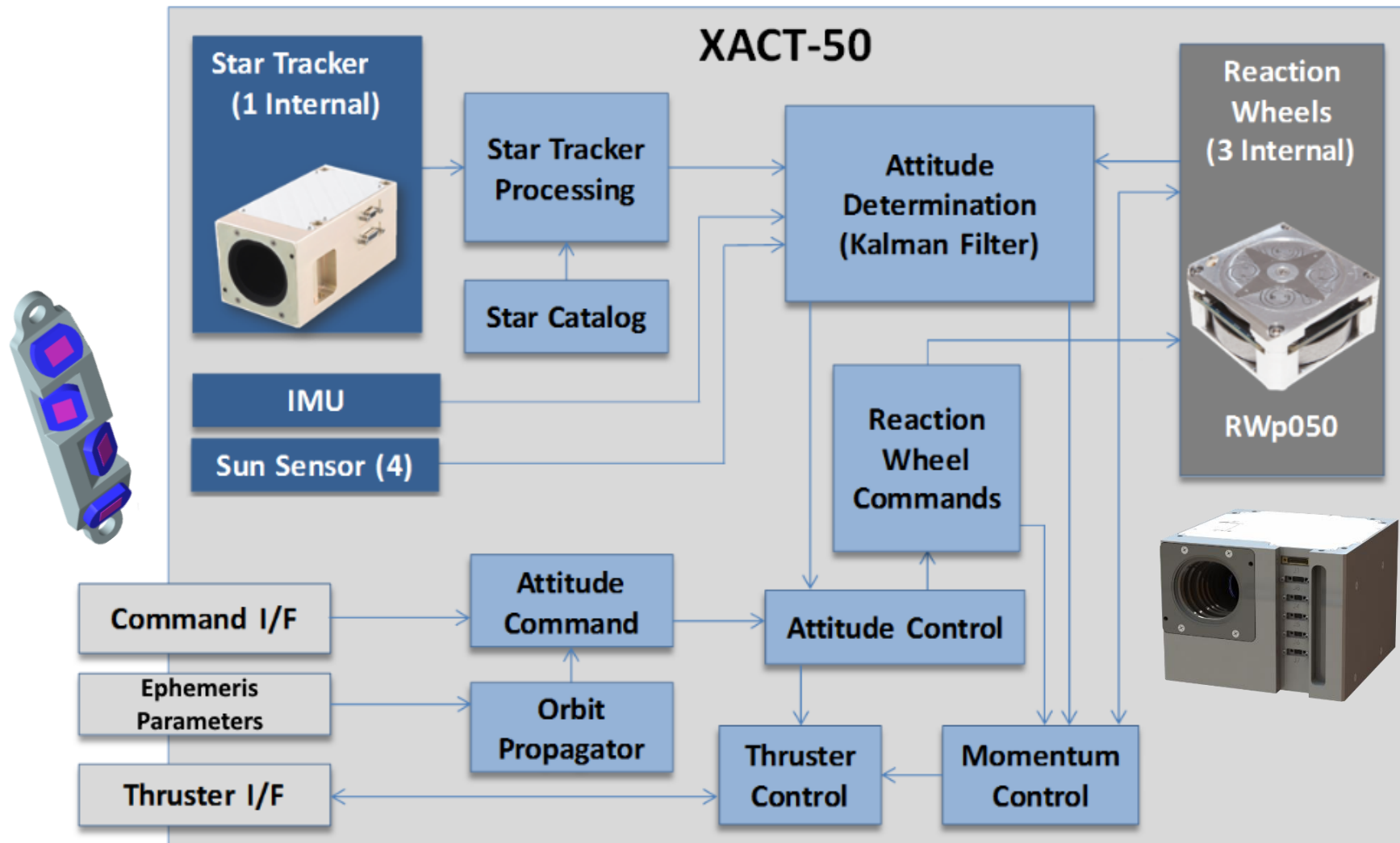
# Lunar Flashlight Ejected from Deployer



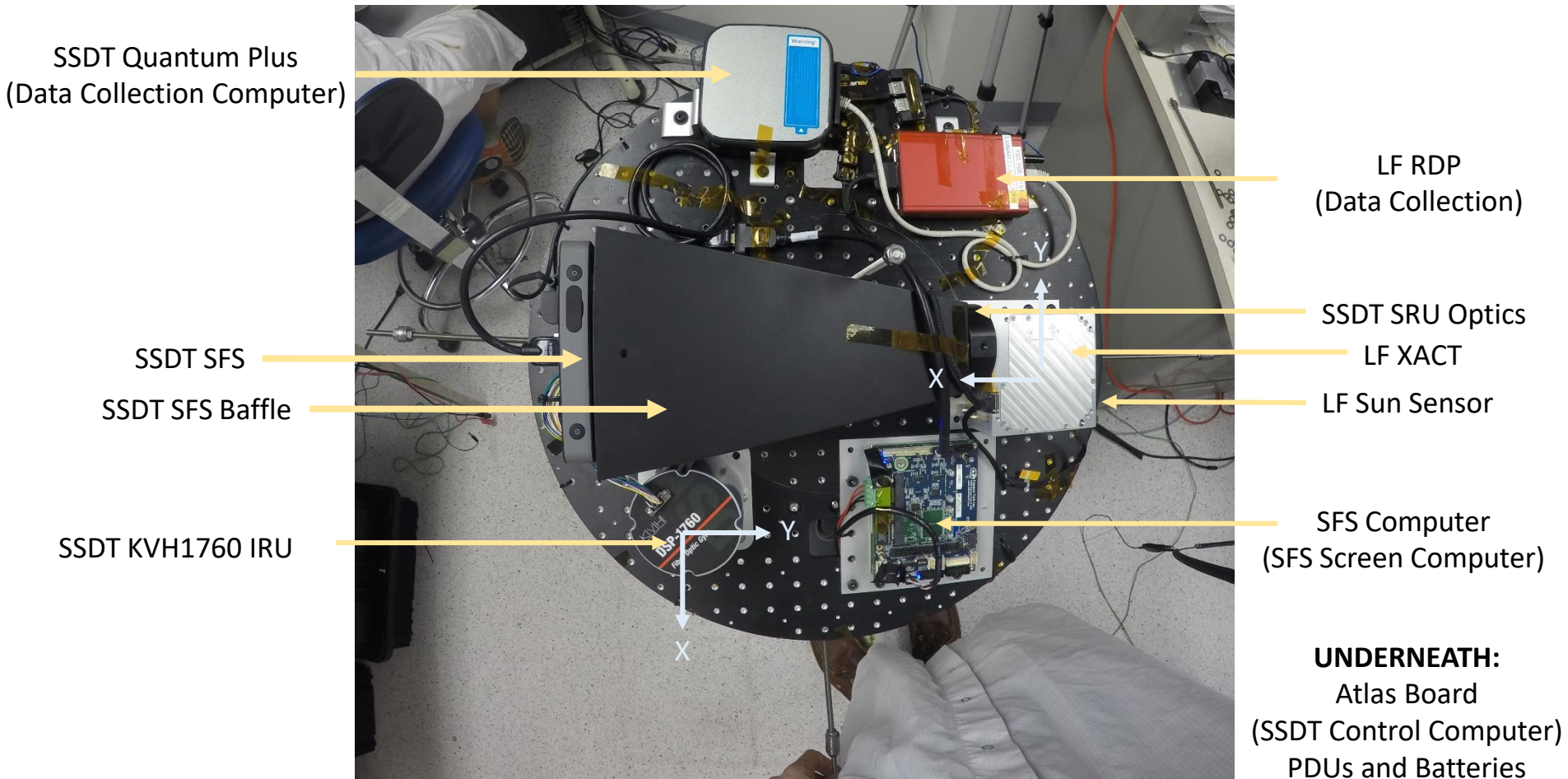
# Lunar Flashlight in Deployed Configuration



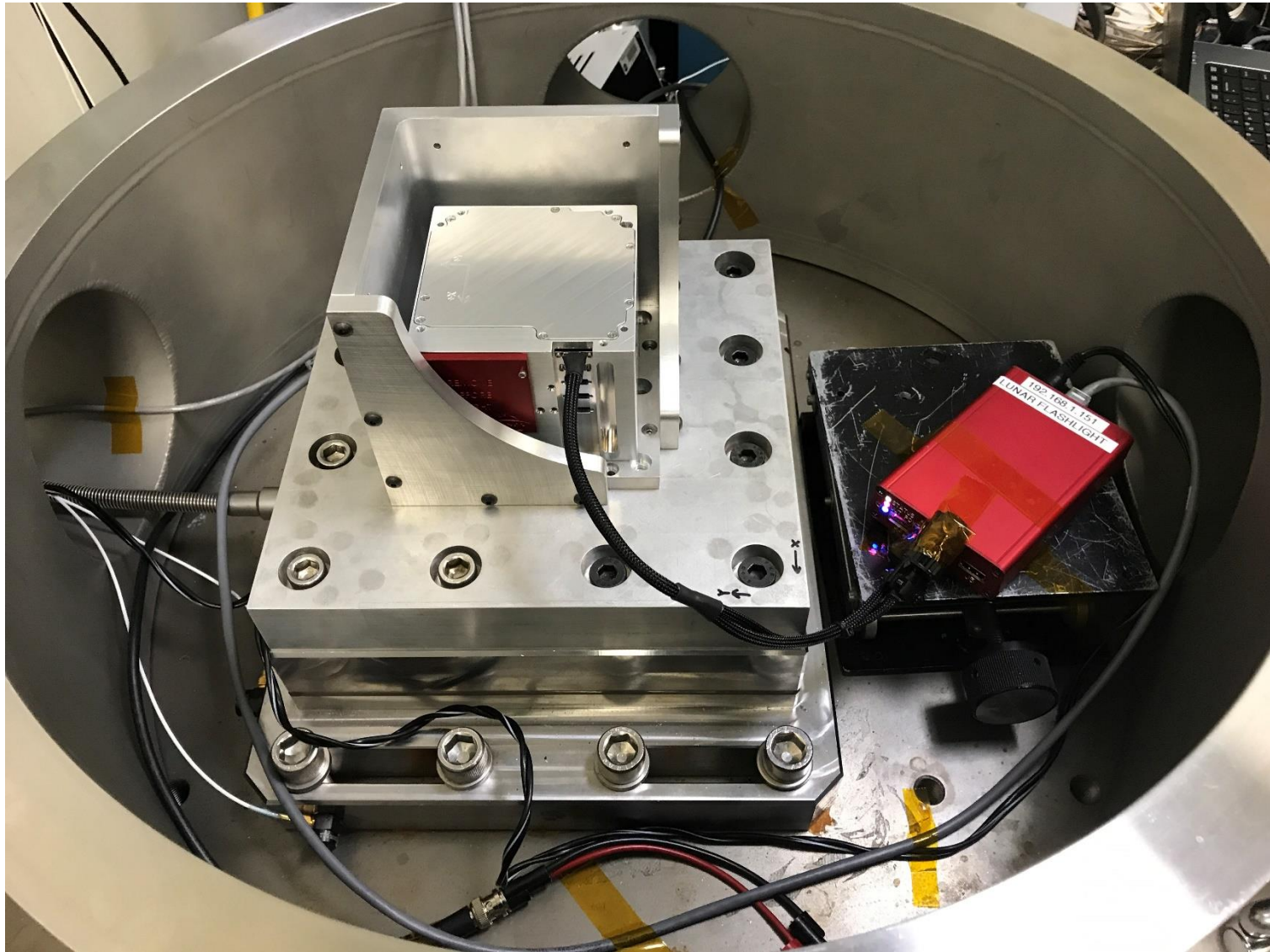
# Lunar Flashlight's XACT-50



# Testing the Lunar Flashlight ACS



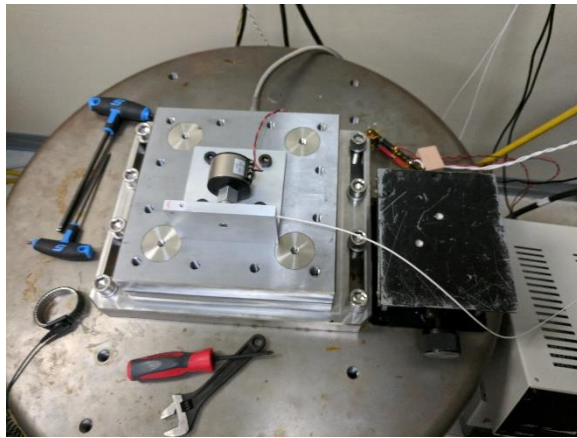
# Jitter Testing (Z-Axis) of Lunar Flashlight Reaction Wheels



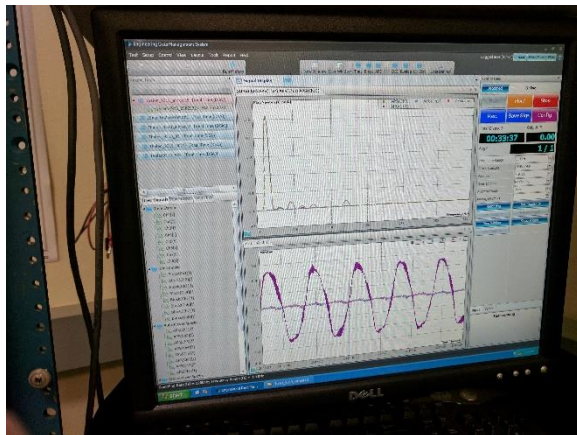
# Calibration of “Truth Sensors”

- Calibrated sensors are necessary to ensure that reported values can be trusted – run separate calibration tests

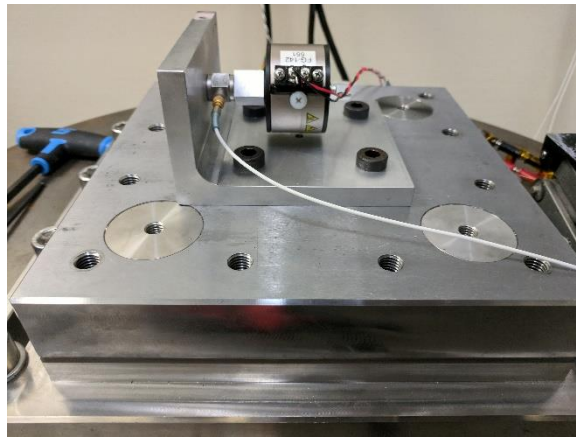
X-Configuration



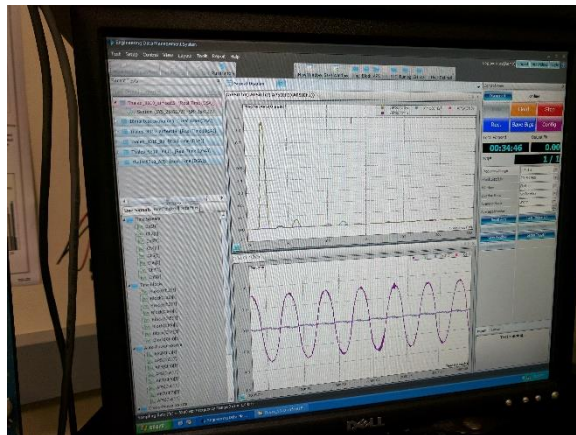
15 Hz



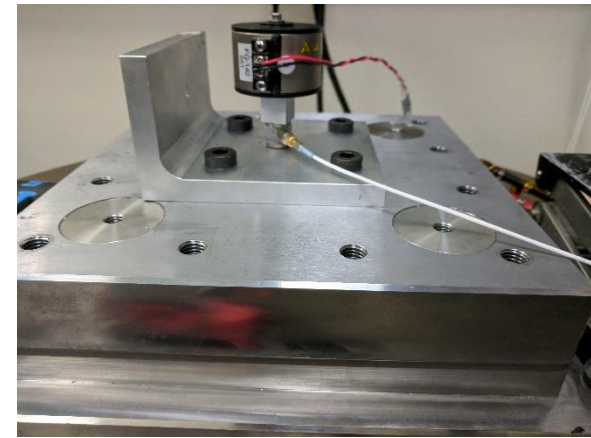
Y-Configuration



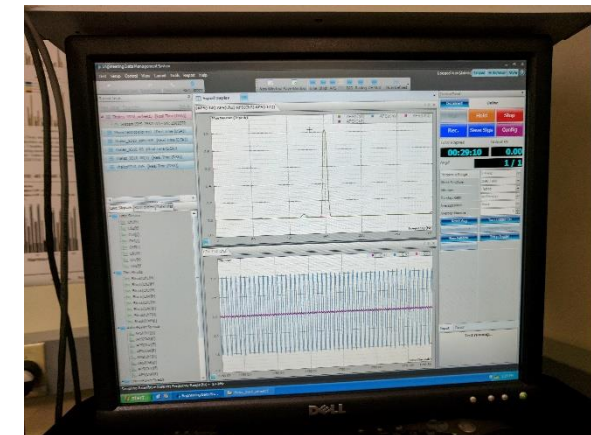
20 Hz



Z-Configuration



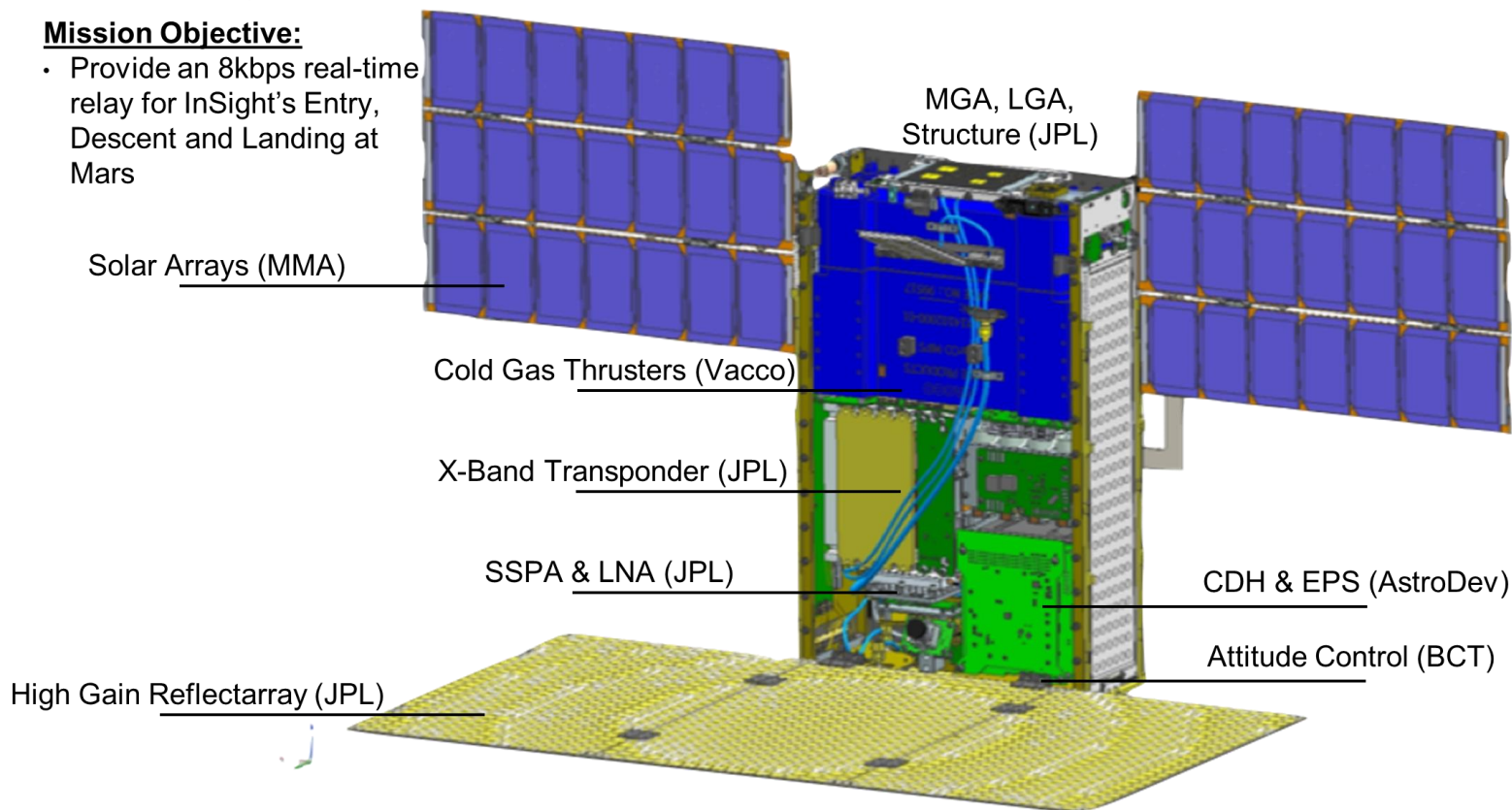
100 Hz



# MarCO

## Mission Objective:

- Provide an 8kbps real-time relay for InSight's Entry, Descent and Landing at Mars



## MarCO Overview:

**Volume:** 2 x 6U (12x24x36cm)

**Mass:** 14.0 kg

## **Power Generation:**

Earth: 35 W

**Data Rates:** 62-8,000 bps

**Delta-V:** >40 m/s

## Software:

FSW: *protos* (JPL)

GSW: AMPCS (NASA/JPL)

## I&T:

In-house S/C I&T, testing,

Tyvak NLAS/Launch Integration

## Operations:

**Primary:** DSN 34m

**EDL:** Madrid 70m

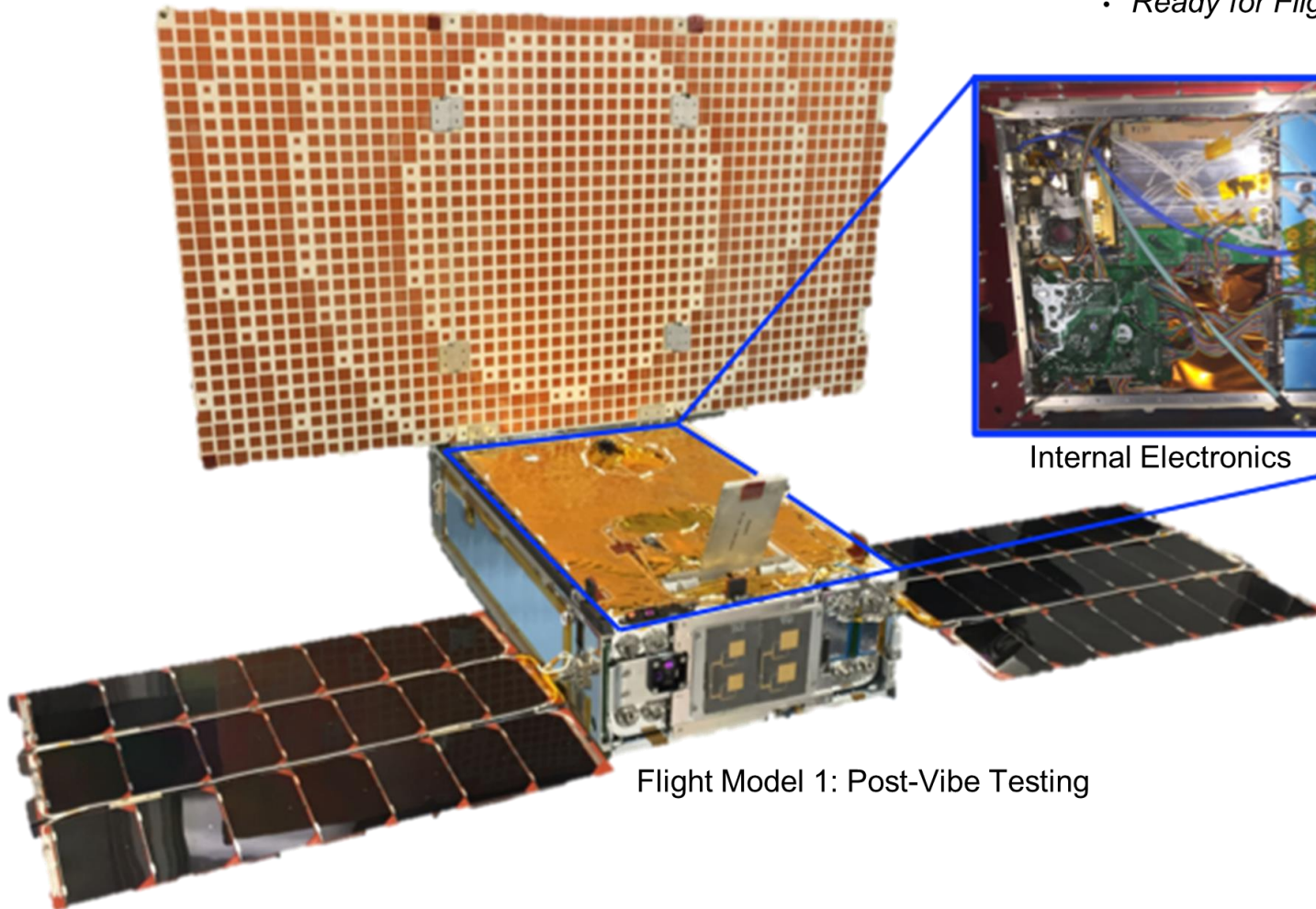
# The MarCO Satellite

## Flight Deployment Check

- *Post Environmental Testing*
- *Ready for Flight!*

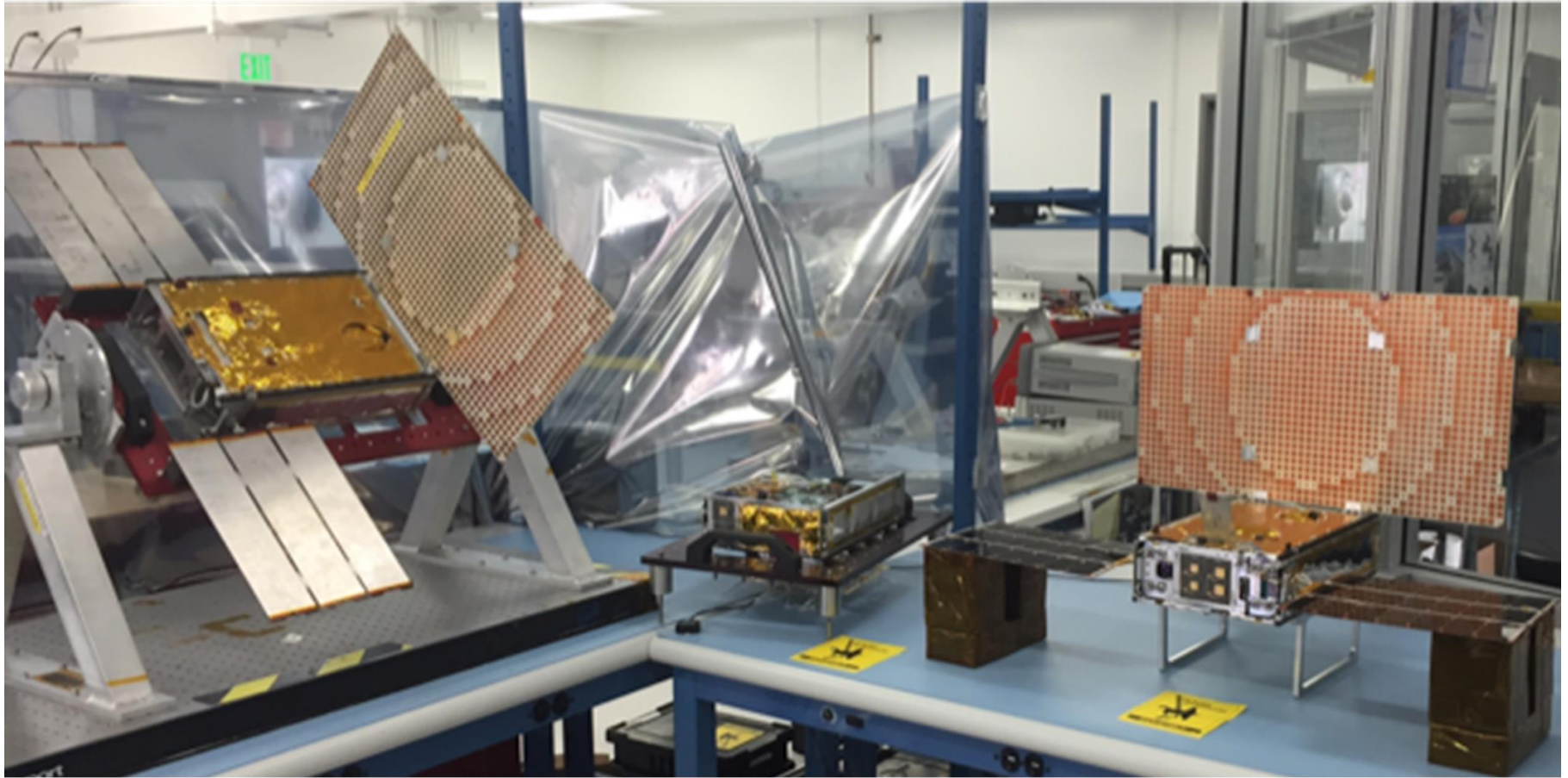


Internal Electronics



Flight Model 1: Post-Vibe Testing

# The MarCO Satellite

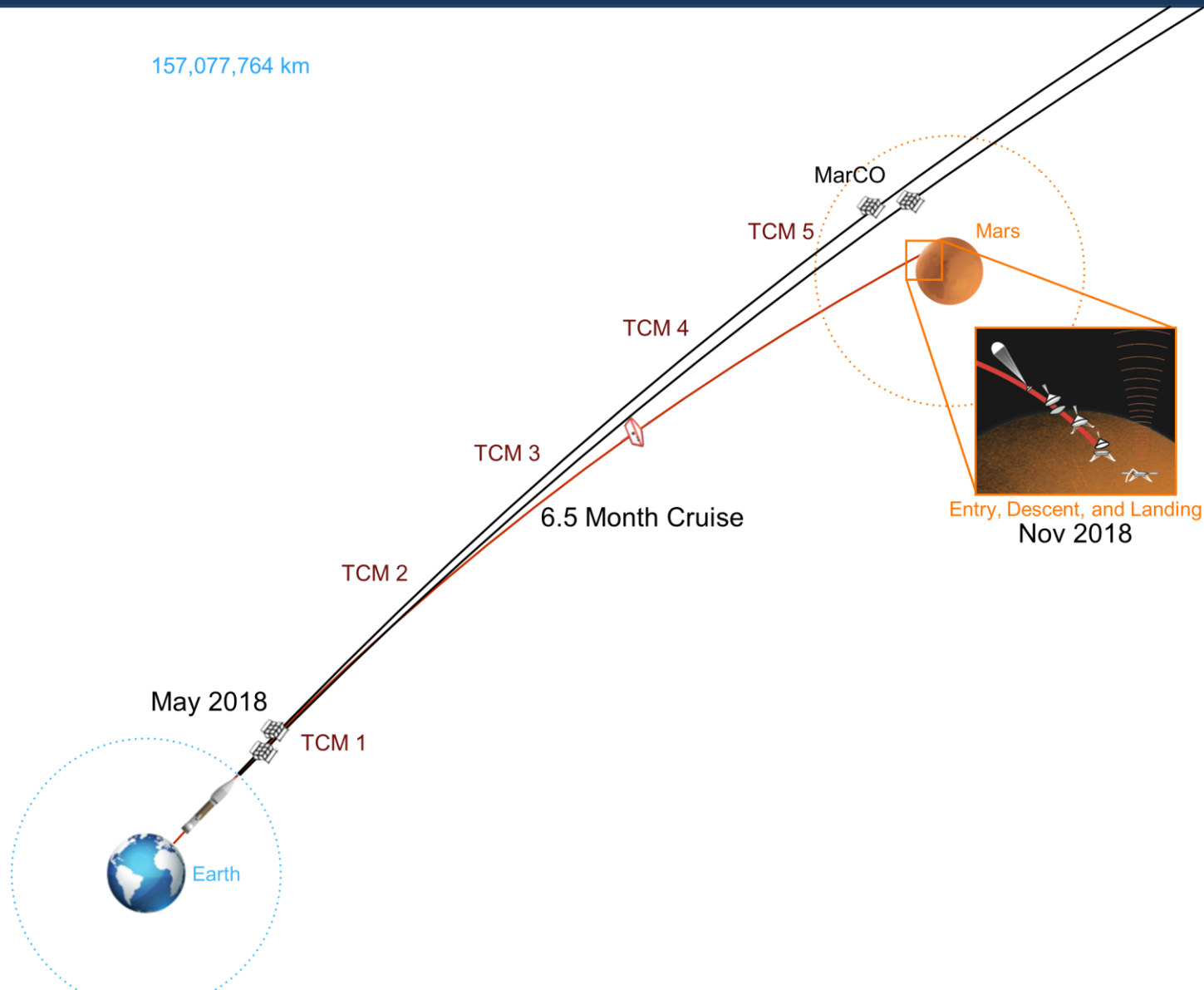


Mechanical  
Model

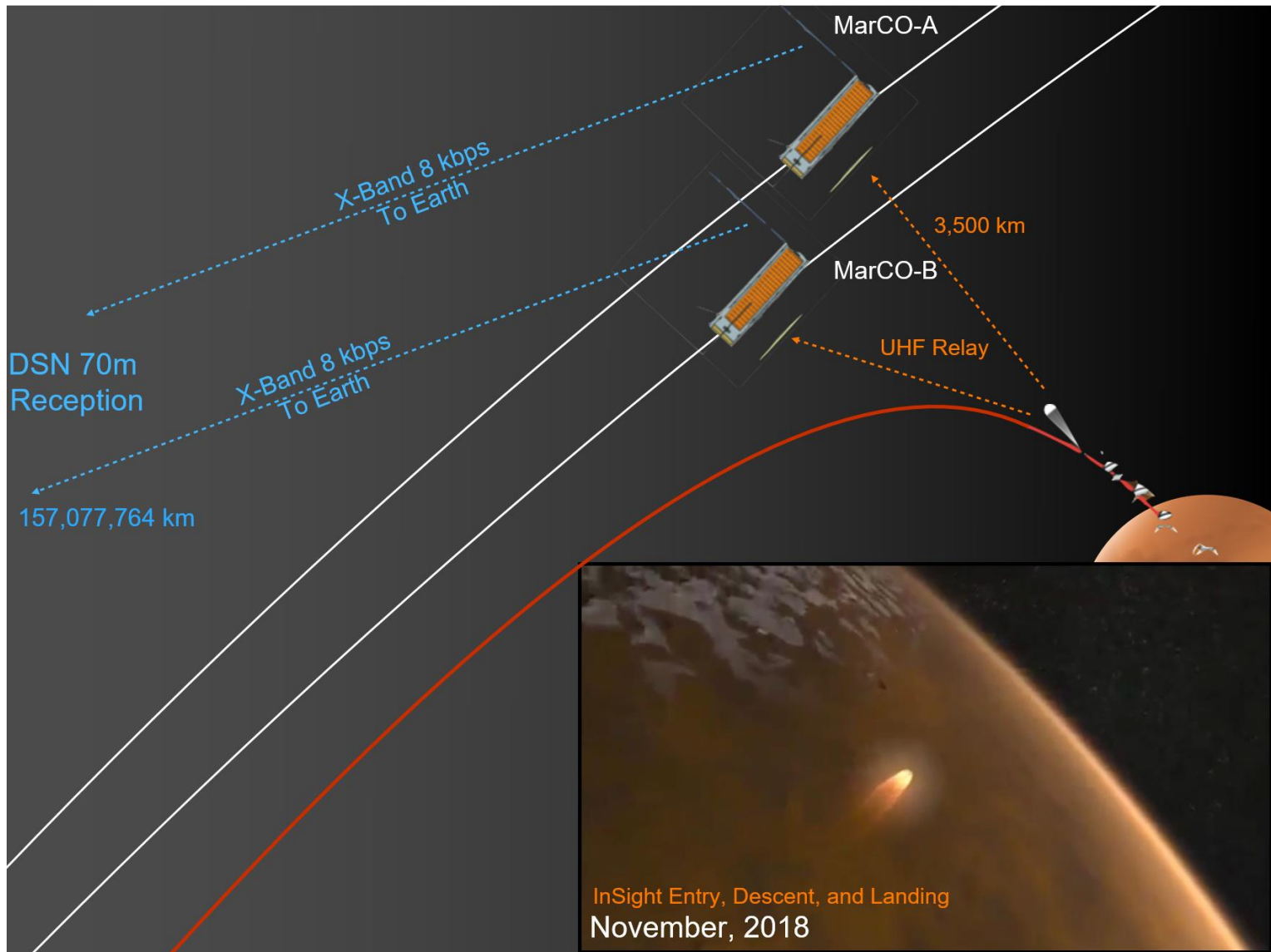
Flight Model 2  
(Access Panels Open)

Flight Model 1  
(Deployed)

# MarCO



# MarCO





# MarCO Deployment



# Concluding Remarks

- Space Systems Engineering
  - Challenging and fun career requiring technical focus
  - The results of your work will be Firsts!
- General Recommendations
  - Find support groups – family, friends, faculty
  - Beyond-classwork experience is highly valued
  - Networking is crucial
  - It's OK to be unsure about your trajectory right now

# Thank You!



Feel free to contact me at [david.c.sternberg@jpl.nasa.gov](mailto:david.c.sternberg@jpl.nasa.gov)

# Contributions

## SDTT: Synchronous Docking to Tumbling Targets

1. **Robust, fuel optimal, low order and computationally efficient trajectories for a representative range of SDTT**
  - a) Identified that a reduced parameterization of the optimal trajectory exists to reduce the computational complexity of deriving the optimal trajectory for rapid optimization
  - b) Found that the fuel minimizing trajectories match the radial and tangential accelerations
  - c) Based upon Finding 1b, formulated a differential equation whose solution results in the optimal approach trajectory
  - d) Assessed the applicability of the Multiple Models for improving robustness to plausible state uncertainties
2. **A process that allows Chaser capability to be evaluated against a family of potential tumbling Targets**
  - a) Defined feasibility space as the set of properties that enable successful SDTT
  - b) Process to identify the Target parameters that a given Chaser can accommodate as well as design a Chaser to accommodate a user-specified set of Target parameters
  - c) Since Target properties are uncertain, developed a sensitivity analysis tool to determine dominant contributors to Chaser design parameter variability
3. **A process for improving a simulation's ability to predict a satellite's on-orbit performance using constrained 1-g testbeds**
  - a) Created degree of freedom constraints to enable unconstrained simulations to provide motion predictions in reduced degree of freedom environments
  - b) Validated the simulation of ground performance by modeling energy dissipation for air bearing systems and through a comparison to ground data
  - c) Validated the simulation of flight performance through a comparison to flight data

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# Challenges Faced in ADR Scenario

- Urgency requires computational efficiency
- Minimize fuel consumption
- **Target properties are initially uncertain**  
[Riesing, Gottlieb, Vallado, Titov, Schueller, Simon]
- Adhere to constraints (e.g. contact velocity and Chaser acceleration)  
[Steigler]
- Coupled translations and rotations  
[Hess, Evans]

## Trajectory Generation:

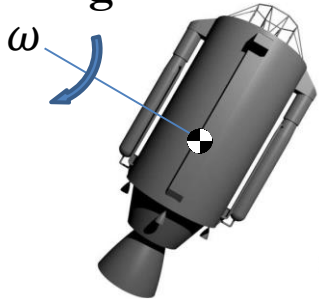
Develop robust, fuel optimal, low order and computationally efficient trajectories for SDTT

Chaser/Target  
Matching

Simulation  
Validation

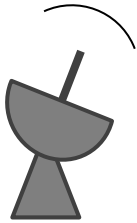
# Sources of Target Uncertainty

## *A Priori* State Estimation Through Remote Sensing

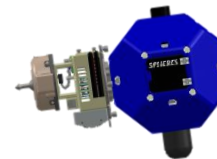
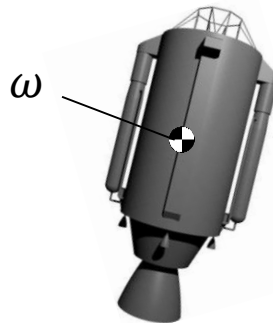


State  $P_0$  with uncertainty bounds

(Gomez Martinez, et al., 2016)

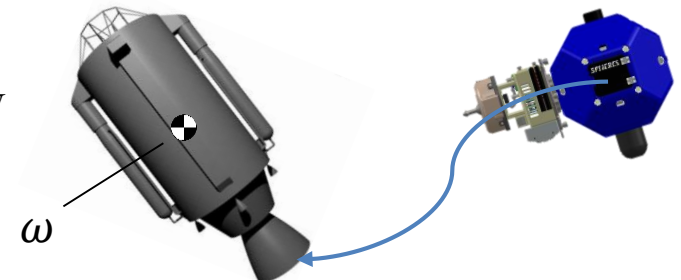


## *In Situ* State Estimation



Approach with Adapted or Robust Synchronous Trajectory

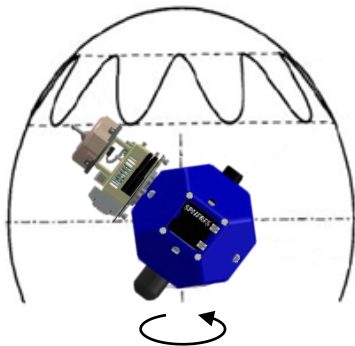
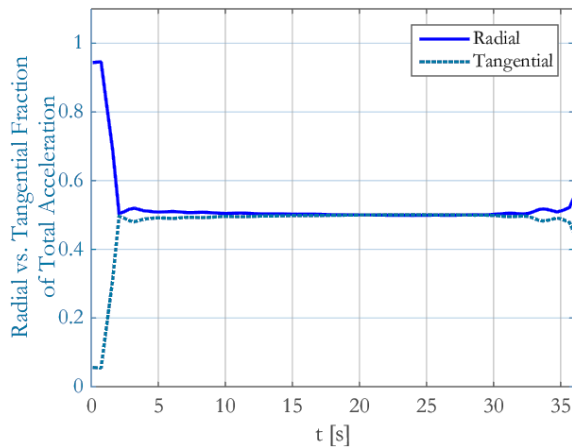
State  $P_0 + \delta$  with reduced uncertainty and adapt or implement robust trajectory



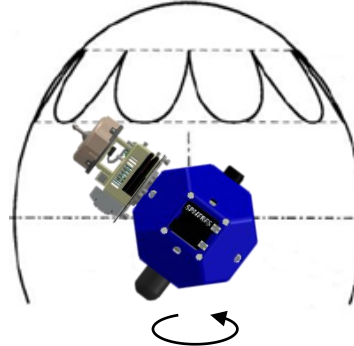
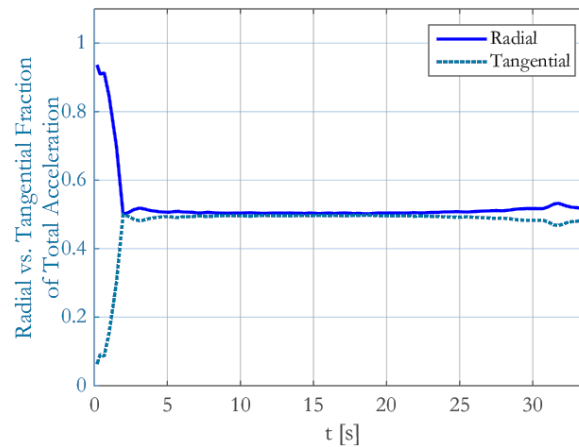
# Trajectory Generation from General Tumble Differential Equation

Thesis Contribution: Formulated a differential equation whose solution results in the optimal trajectory

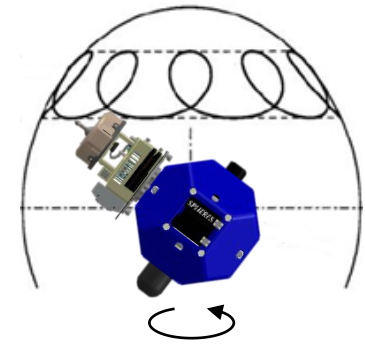
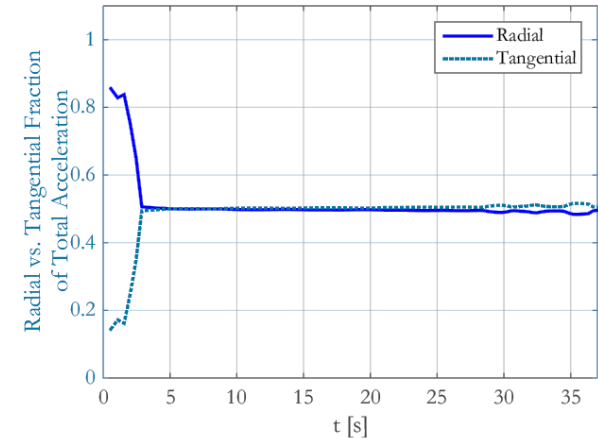
## Unidirectional Precession



## Cuspidal Precession



## Looping Precession



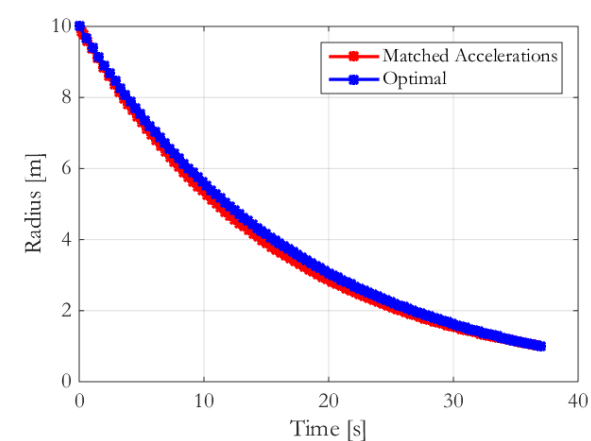
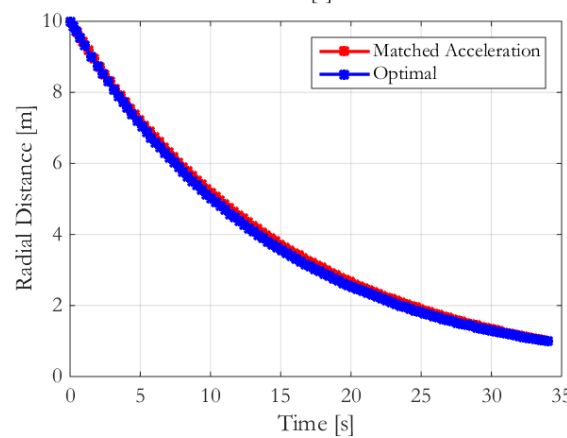
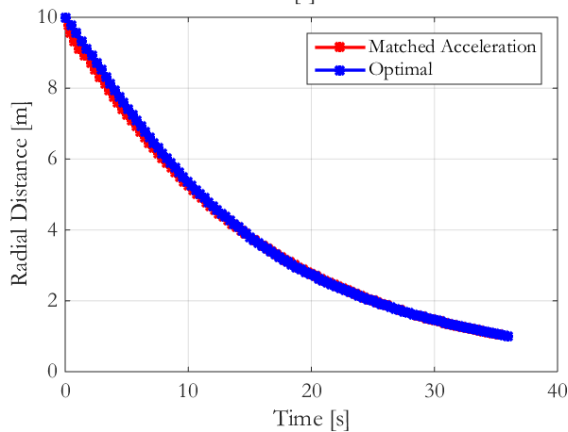
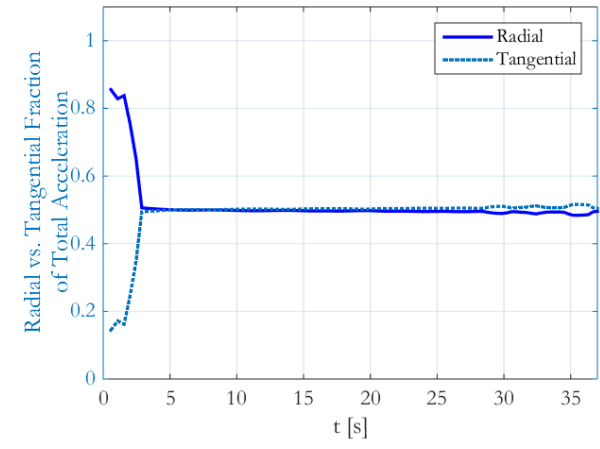
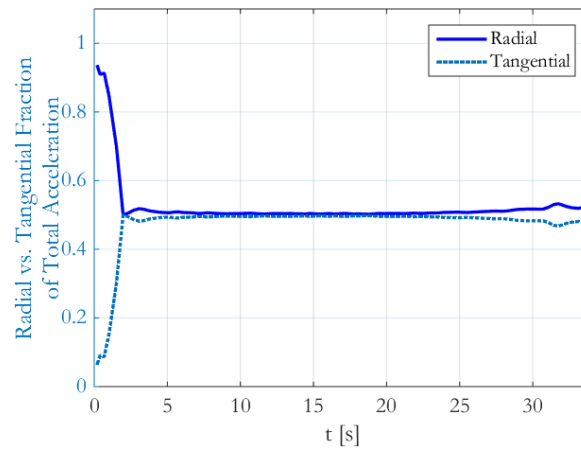
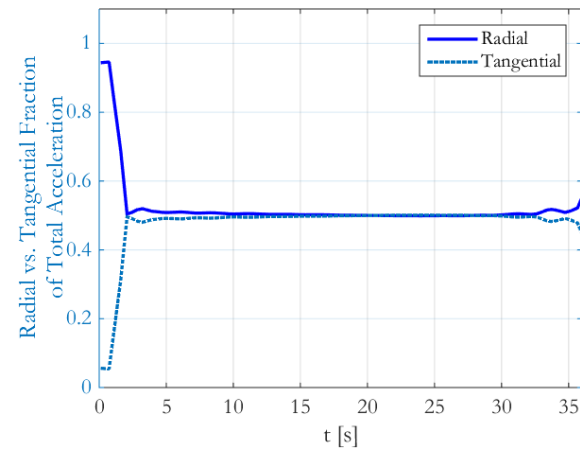
# Trajectory Generation from General Tumble Differential Equation

Thesis Contribution: Formulated a differential equation whose solution results in the optimal trajectory

## Unidirectional Precession

## Cuspidal Precession

## Looping Precession



$\Delta V$  difference: 2%

$\Delta V$  difference: 4%

$\Delta V$  difference: 3%

# Multiple Model Approach for Robust Trajectory Generation

- Sacrifices nominal performance for robustness over a range of uncertainty [MacMartin, Liu]

$$\min_T \sum_{i=1}^n \frac{\Delta V_i(M, T) w_i}{|W|}$$

$T = [T_1, \dots, T_p]$  trajectory parameters

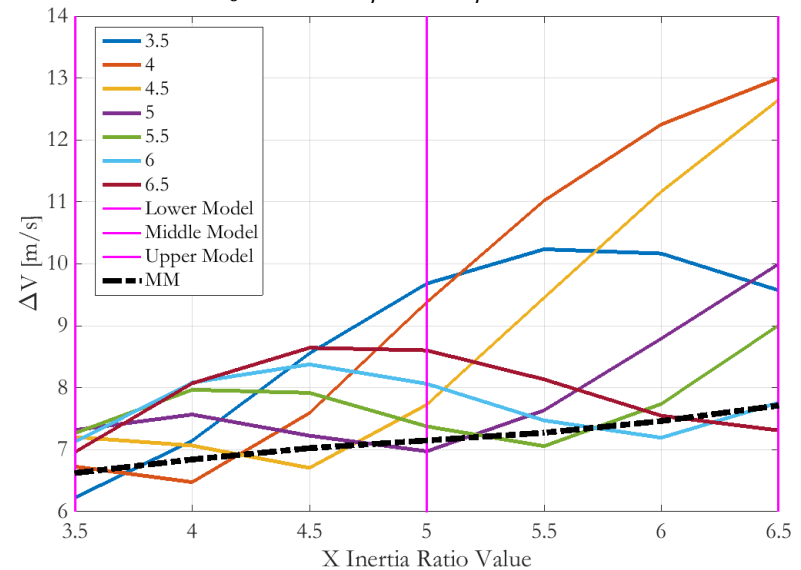
$M = [m_1, \dots, m_n]$ ,  $m_i = [t_f, r_0, r_f, \omega^T, J^T]$  models

$W = [w_1, \dots, w_n]$  weights with probability  $w_i = P(m_i)$

$|\omega| = 5 \text{ deg/s}$ ,  $\hat{\omega}_0 = [0 \ 0.1 \ 1]$

$r_0 = 10 \text{ m}$  to  $r_f = 1 \text{ m}$ ,  $t_f = 5 \text{ min}$

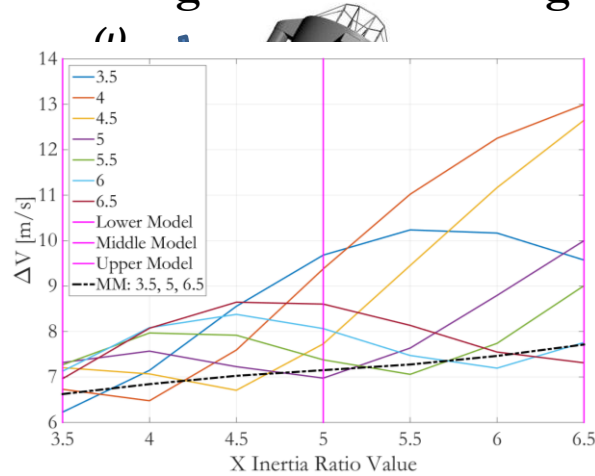
- Example: axisymmetric body, varying  $J = [X \ X \ 1]'$ 
  - MM trained on  $X = \{3.5, 5, 6.5\}$
- MM provides flattened  $\Delta V$  cost curve across inertia ratio range



Thesis Contribution: Formulated the Multiple Model approach for robust trajectory generation for plausible property uncertainties

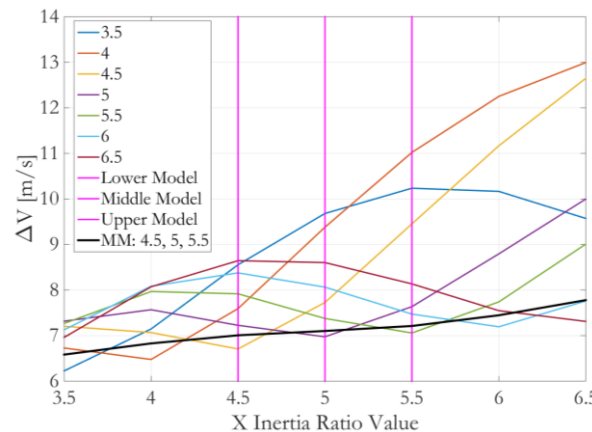
# Robustness to Target Uncertainty

## *A Priori* State Estimation Through Remote Sensing



with uncertainty bounds

## *In Situ* State Estimation

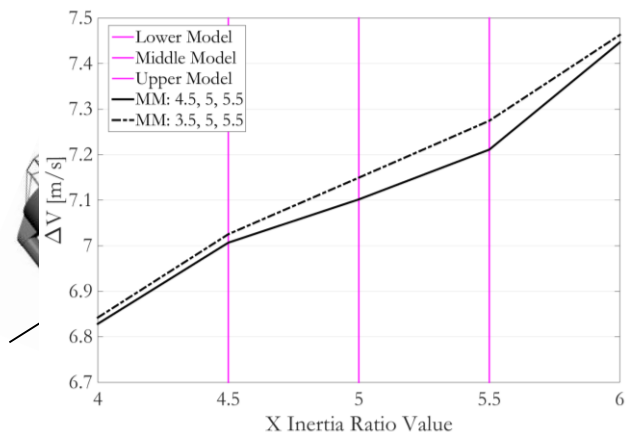


State  $P_0$   
and adapt or implement robust trajectory

- Narrower range of possible inertia ratios

Developed robust, fuel optimal, low order and computationally efficient trajectories for a representative range of SDTT

## Approach with Adapted or Robust Synchronous Trajectory



# Chaser/Target Matching: Defining Methodology

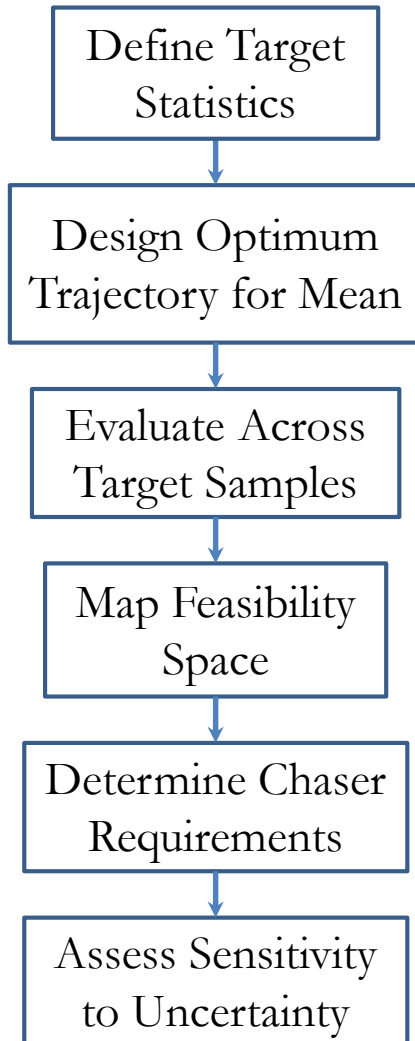
- Problem Statement: Determine the feasibility of docking to a Target with uncertain properties

		Target Selection	
		Known	Unknown
Chaser Design	Known	Can the proposed docking mission be conducted successfully?	Given a known Chaser, what are the possible Targets with which a docking can be achieved?
	Unknown	In order to dock to Target, to which parameters is the Chaser most sensitive?	How well must the Target be defined for a Chaser with minimum required margins to be low risk?

- Feasibility space: The set of parameter values over which a given Chaser can achieve a soft dock

Target Parameters	$r_f$	$\omega$	$J$
Chaser Parameters	$T$	$r_0$	
Performance Metrics	$a_{max}$	$\Delta V$	$t_f$ $v_f$

# Chaser/Target Matching: Defining Methodology



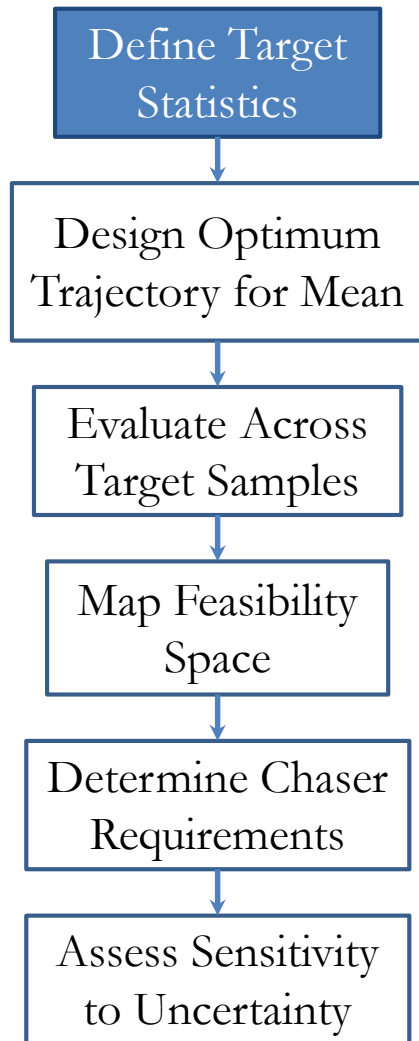
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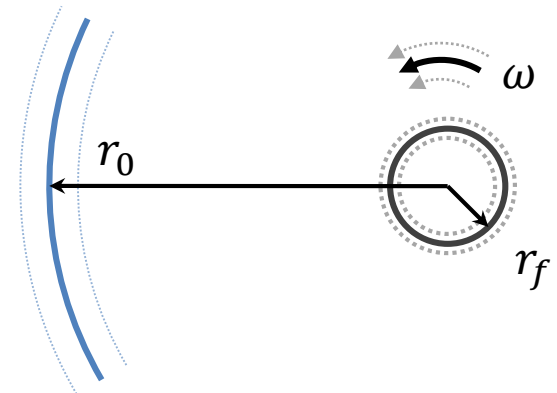
Target Parameters	$r_f$	$\omega$	$J$
Chaser Parameters	$T$	$r_0$	
Performance Metrics	$a_{max}$	$\Delta V$	$t_f$ $v_f$

# Chaser/Target Matching: Defining Target Statistics



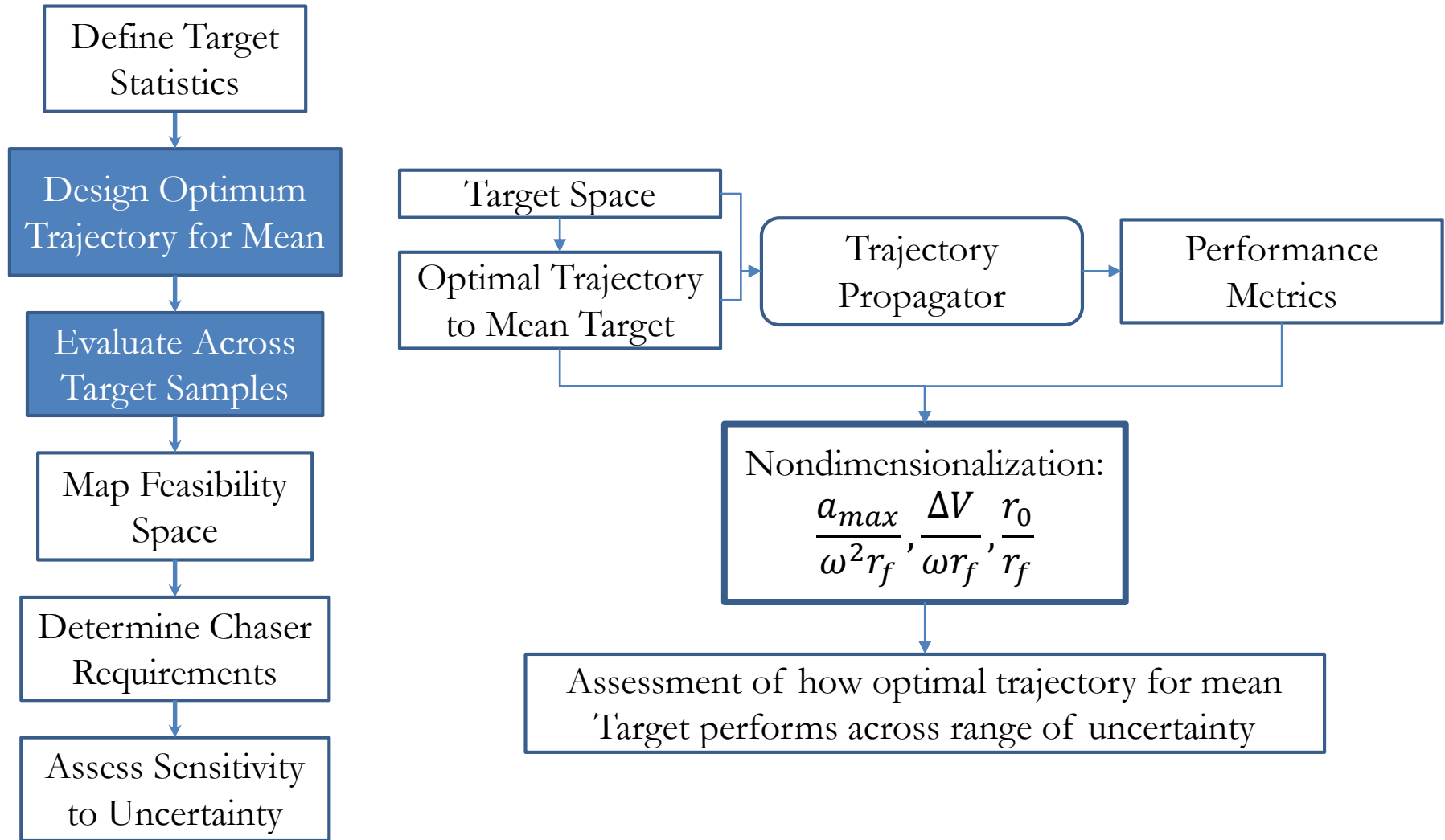
Target space defined by level of uncertainty

- Consider uncertainty in:
  - Parameters that describe motion of docking port:  $r_f, \omega, J$
  - Knowledge of initial rendezvous location:  $r_0$
- Example case with uniform distributions:
  - $r_f = 1 \pm 0.1$  m
  - $\omega = 5 \pm 1$  deg/s
  - $J = [1 \ 1 \ 1]$
  - $r_0 = 10 \pm 0.25$  m

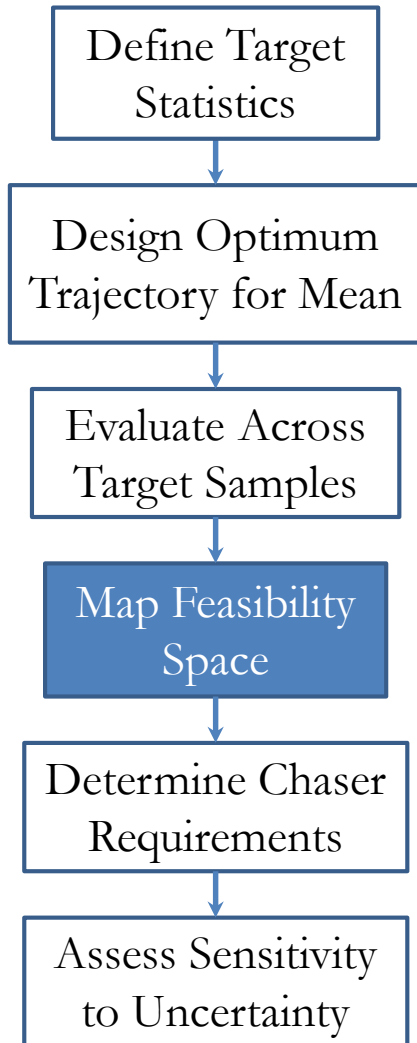


# Chaser/Target Matching:

## Evaluate Trajectory for Mean on All Target Samples

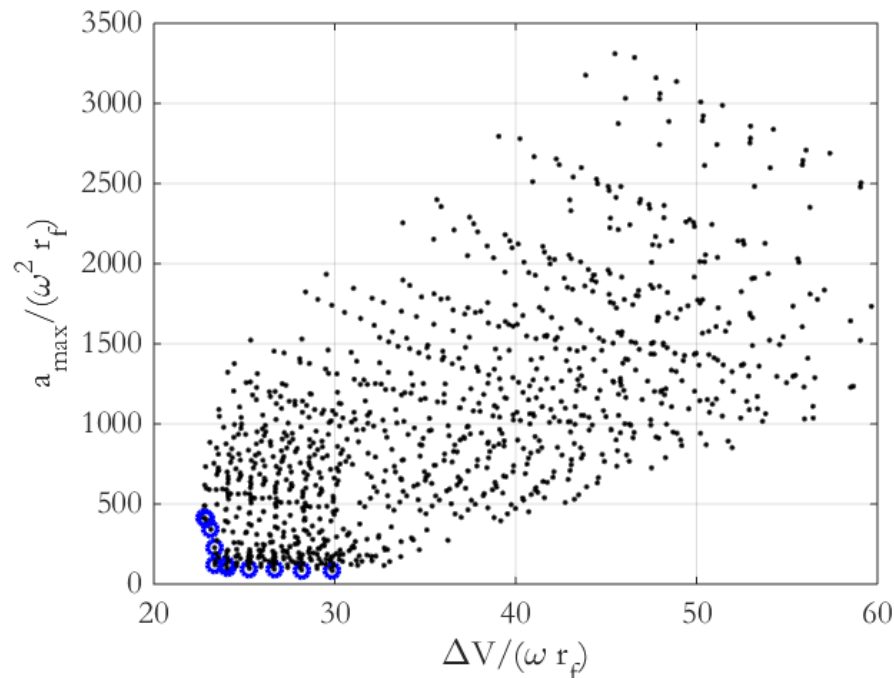


# Chaser/Target Matching: Mapping Feasibility Space

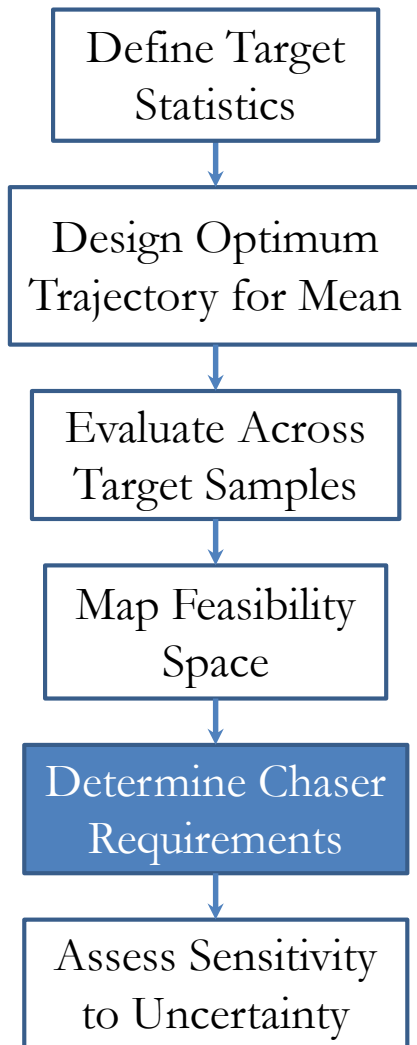


Thesis Contribution: Mapped feasibility space to study Chaser design requirements

- Shape identifies demands on Chaser satellite from Target's uncertainty while using fuel optimal trajectory
- Pareto points represent minimum Chaser performance requirements

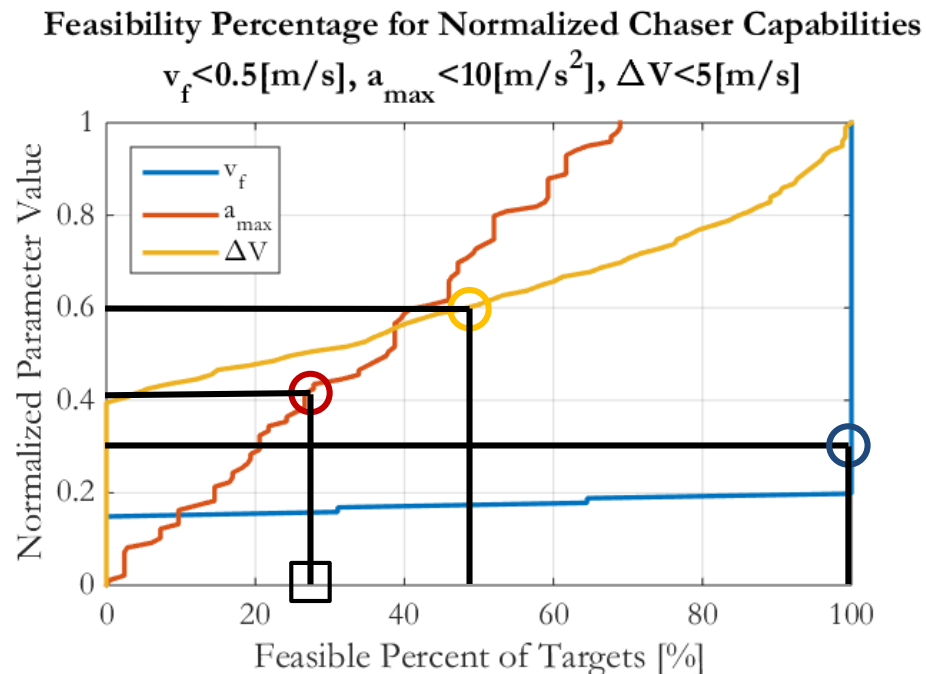


# Chaser/Target Matching: Determining Chaser Requirements

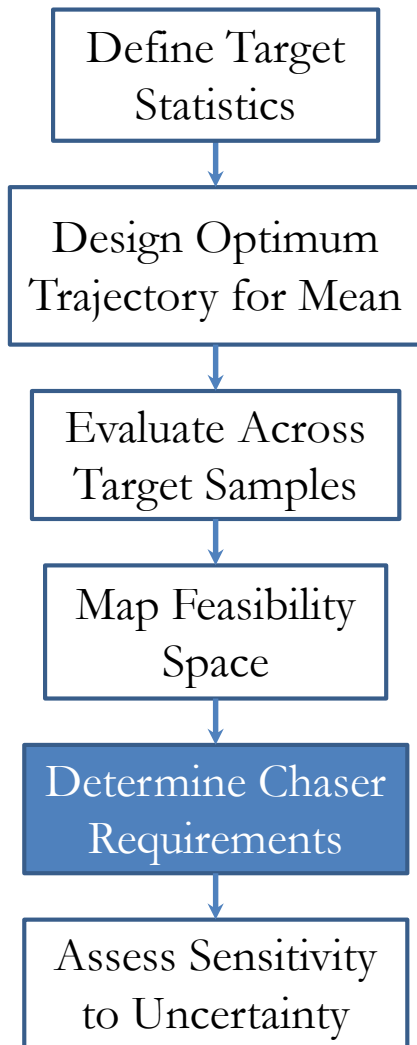


Thesis Contribution: Mapping between Target property and Chaser design spaces

- Market Analysis: Identifying the Target samples to which an existing Chaser can feasibly dock
  - Input: Chaser design
  - Output: Percentage of Targets

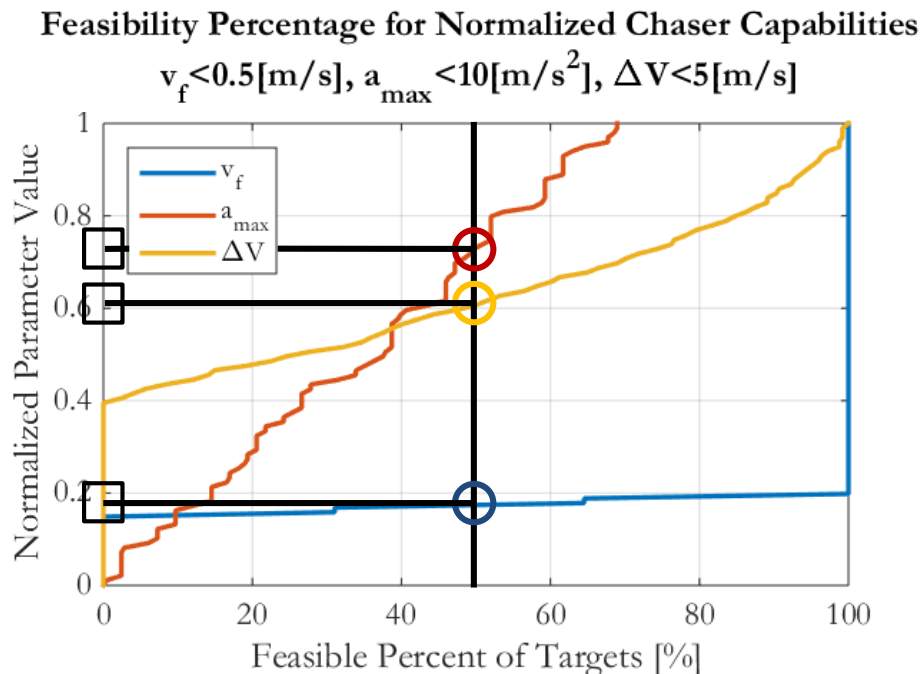


# Chaser/Target Matching: Determining Chaser Requirements

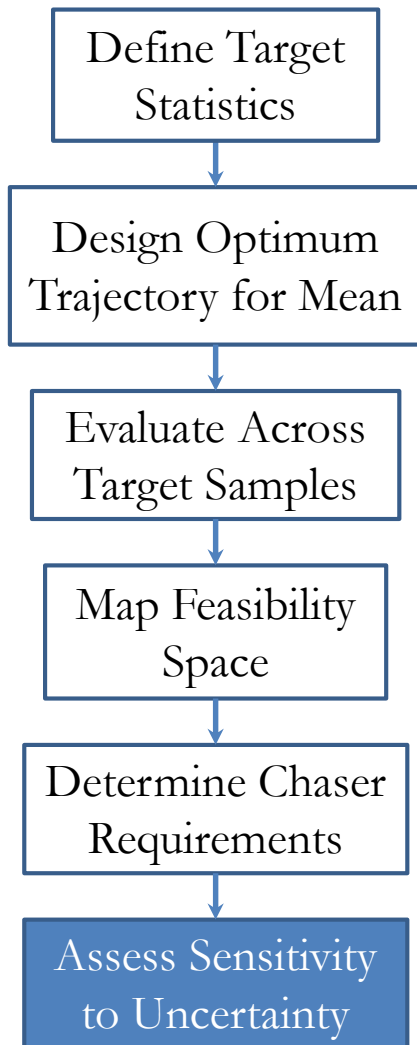


Thesis Contribution: Mapping between Target property and Chaser design spaces

- Market Capture: Determining the Chaser design for docking with a desired percentage of the Target samples
  - Input: Percentage of Targets
  - Output: Chaser requirements



# Chaser/Target Matching: Sensitivity to Uncertainty

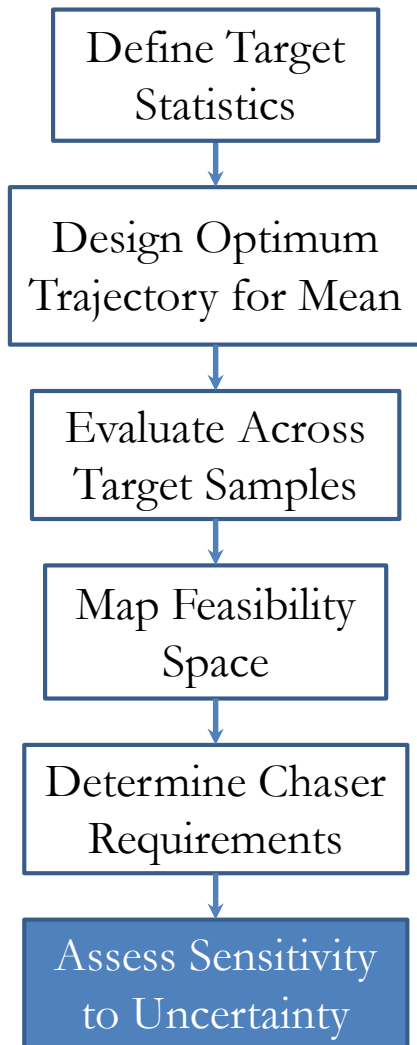


Thesis Contribution: Developed a sensitivity analysis tool for determining the Target properties that most affect the Chaser design

- Compute sensitivity metrics based on simulation outputs at selected trajectory
  - Latin Hypercube sampling
  - Output Metrics
    - $\Delta V$  required
    - Relative contact velocity
    - Time until docking
    - Docking success

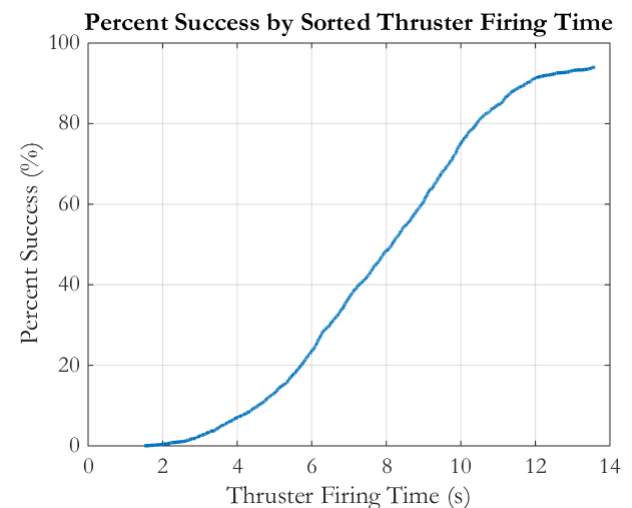
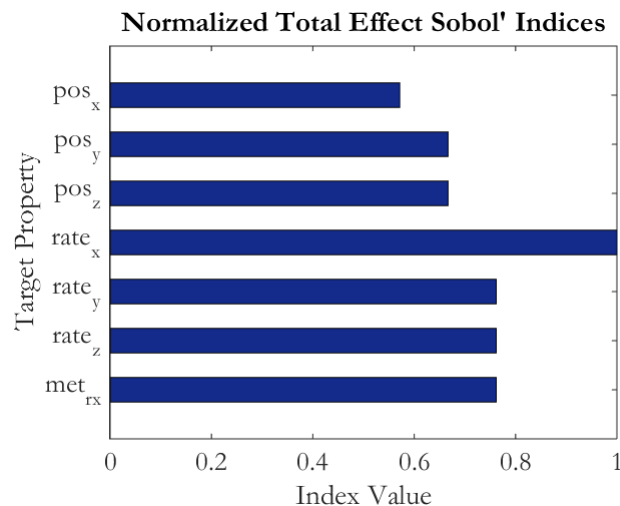
Variable	Distribution
Initial Separation Distance ( $r_0$ )	0.6m
Docking Port Distance ( $r_f$ )	0.251m
<b>Initial Position</b>	U[ <b>mean</b> $\pm$ <b>5</b> ]cm
Initial Linear Velocity	Stationary
Initial Attitude	[1;0;0;0]
<b>Initial Angular Rate</b>	U[ <b>mean</b> $\pm$ <b>5</b> ]deg/sec
Target Satellite Mass	5.984kg
<b>Metrology Loss Level</b>	U[ <b>3, 50</b> ]%
Metrology Noise Standard Deviation	$3.3 \times 10^{-3}$ m

# Chaser/Target Matching: Sensitivity to Uncertainty



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# Challenges Faced in ADR Scenario

- Urgency requires computational efficiency
- Minimize fuel consumption
- Target properties are initially uncertain  
[Riesing, Gottlieb, Vallado, Titov, Schueller, Simon]

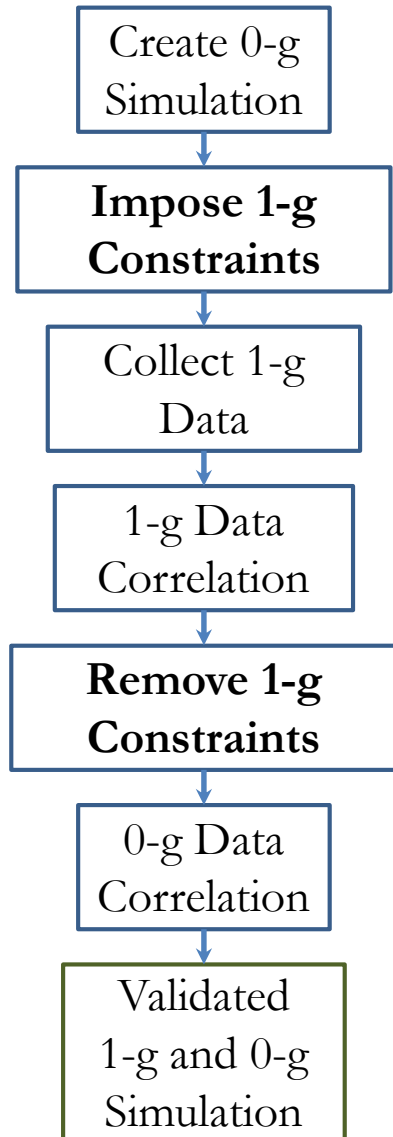
Trajectory  
Generation

Chaser/Target  
Matching

- Adhere to constraints (e.g. contact velocity and Chaser acceleration)  
[Steigler]
- **Coupled translations and rotations**  
[Hess, Evans]

**Simulation Validation:**  
Developed a process for improving  
a simulation's ability to predict a  
satellite's on-orbit performance

# Validating 0-g Simulation through Ground Hardware Testing



## Problem Statement:

Obtain validated models of the 1-g and 0-g operating environments and of the Chaser's hardware and software

## Requires:

- Constraining satellite dynamics
- Ground environment modeling
- Simulation tuning using ground data (dynamics and environment) and flight data (environment)

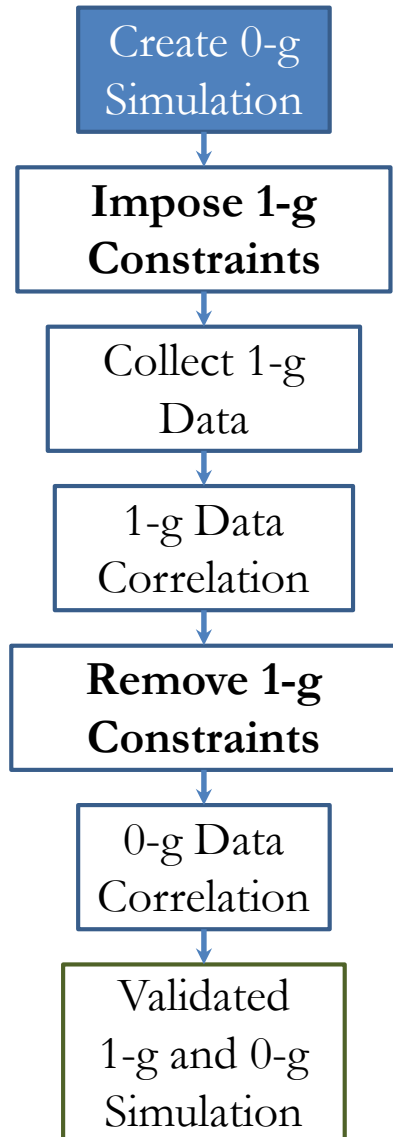
## Example:

JPL Small Satellite Dynamics Testbed

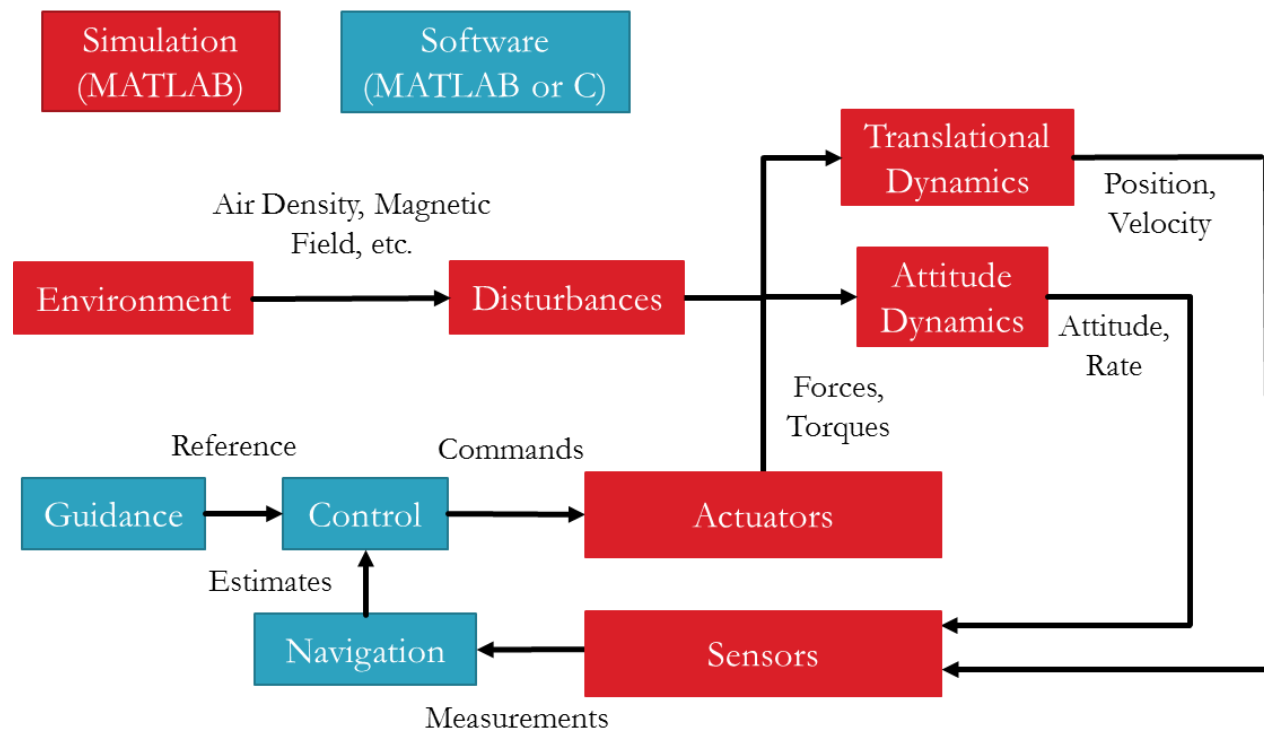


# 0-g Simulation Validation with 1-g Testbeds: NASA

## Create 0-g Simulation

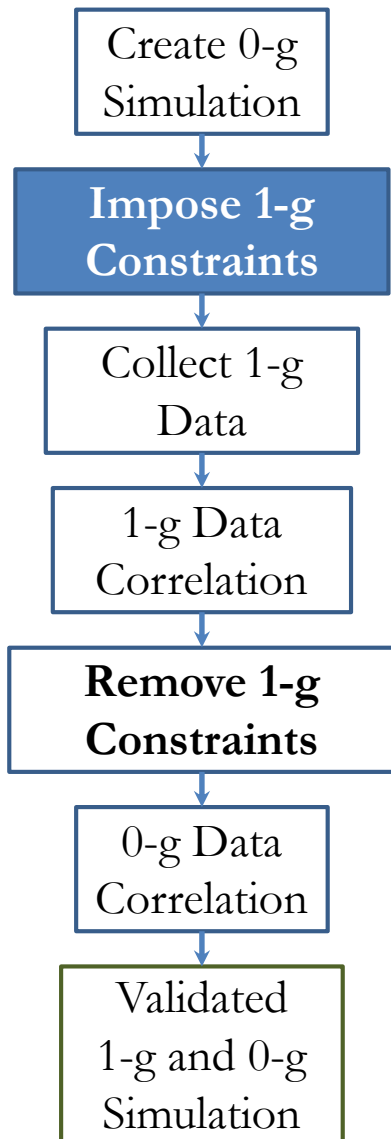


### JPL Small Satellite Dynamics Testbed's Simulation



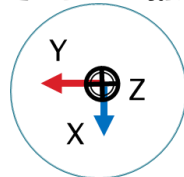
0-g Simulation Validation with 1-g Testbeds: 

## Impose Ground Constraints

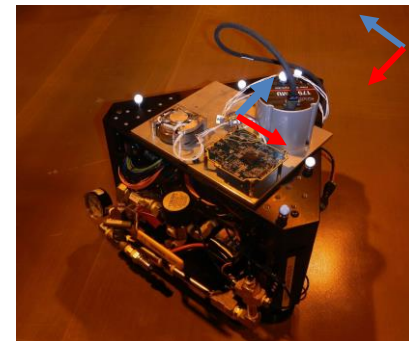
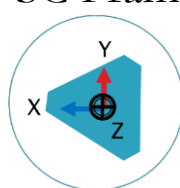


- Define reference frames for constrained operation

LAB Frame



SC Frame



- Determine environmental effects
  - Couette dissipation for air bearings

$$F_{Couette}^{LAB} = \mu_{lin} v^{LAB}$$

- Propagate motion in LAB frame

$$a^{SC} = [\dot{v}^{SC}(2,1); 0] - \vec{g}$$

$$v^{LAB} = q_{SC}^{LAB*} \otimes v^{SC} \otimes q_{SC}^{LAB}$$

 $F_{Couette}^{LAB}$ 

Couette dissipation

 $\mu_{lin}$ 

Couette constant

 $v^{LAB}$ 

Velocity in LAB frame

 $a^{SC}$ Projected acceleration  
in SC frame $\dot{v}^{SC}$ Velocity derivative in  
SC frame $\vec{g}$ 

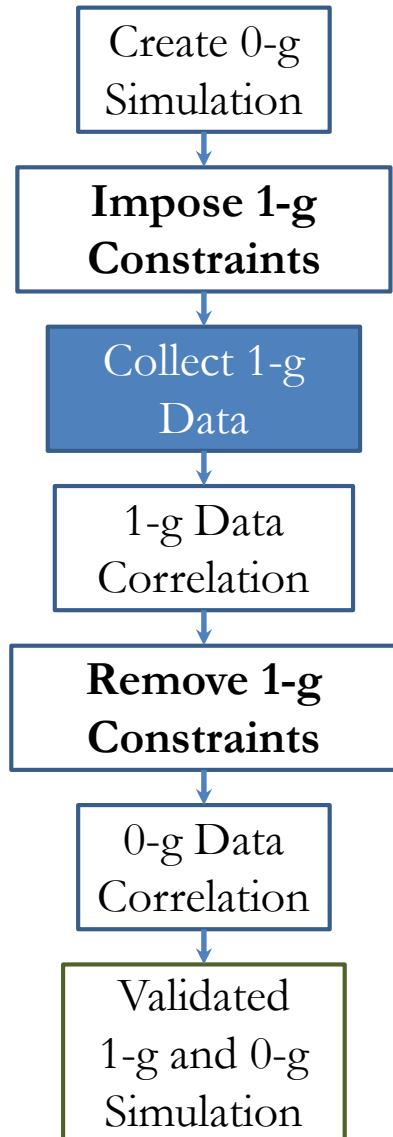
Gravity vector

 $q_{SC}^{LAB}$ Quaternion from SC  
to LAB frame $v^{SC}$ 

Velocity in SC frame

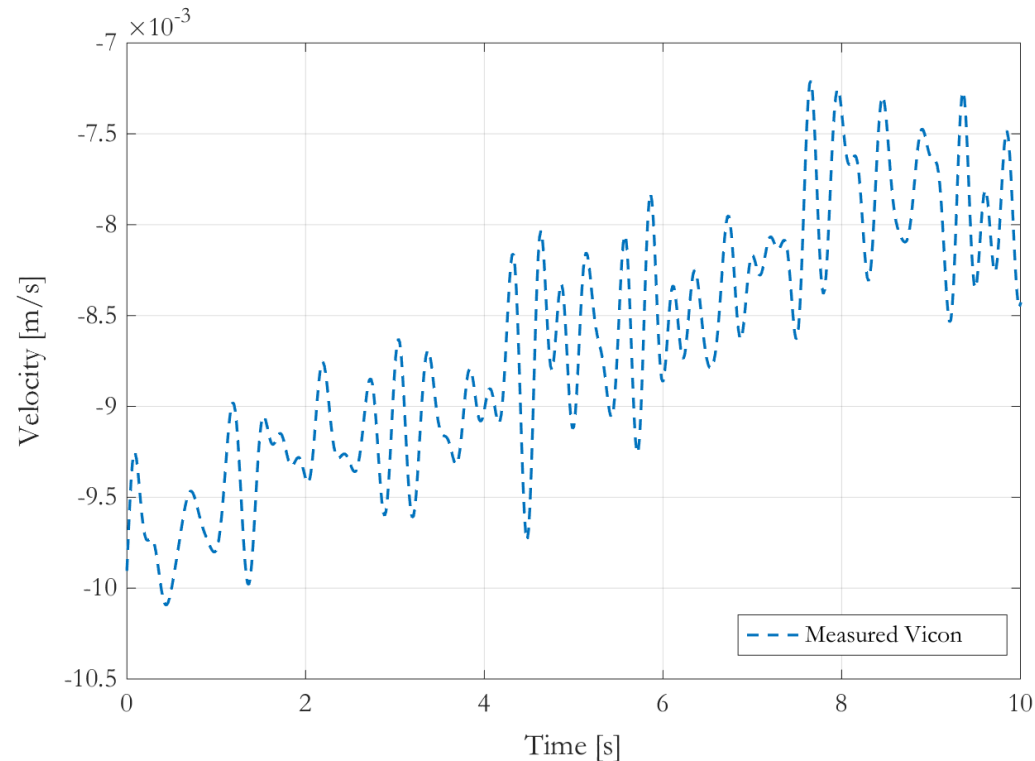


## Perform 1-g Testing



Collect 1-g data to determine parameters of 1-g environment

Translation of Planar Sled on Flat Floor

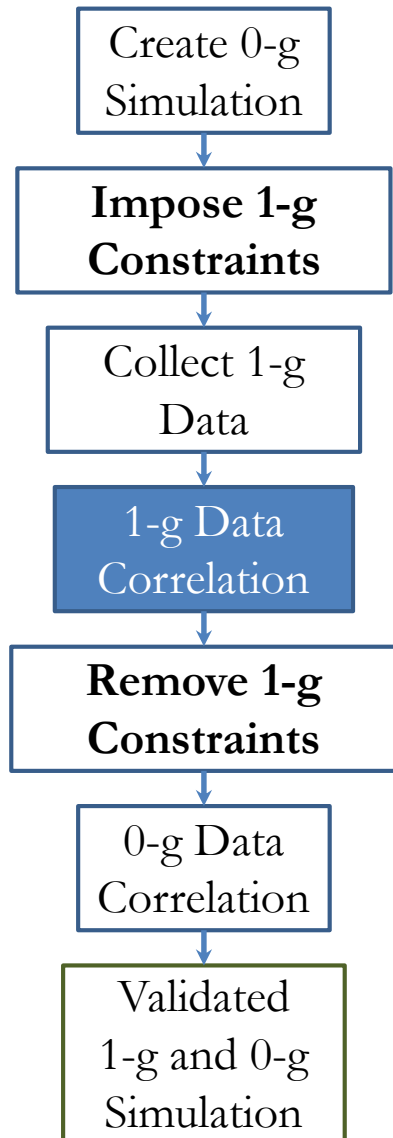


Data acquisition from 1-g testbed captures operating dynamics and environment



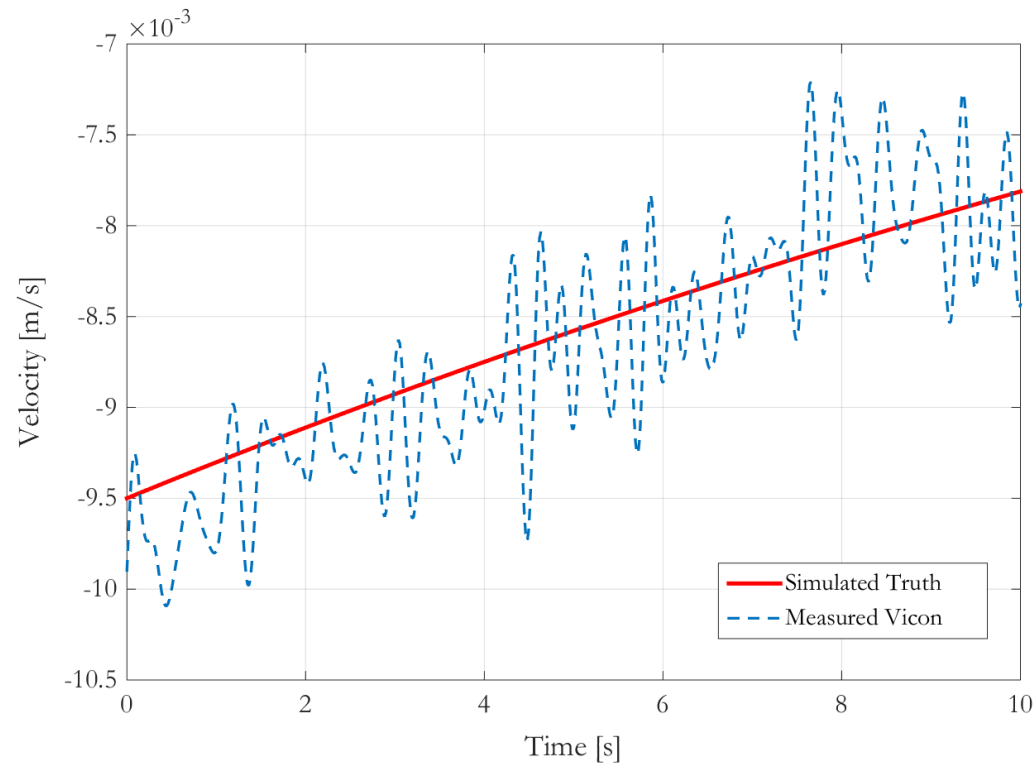
# 0-g Simulation Validation with 1-g Testbeds: NASA

## 1-g Model-Data Correlation



Tune simulation using acquired 1-g environmental parameters

Translation of Planar Sled on Flat Floor

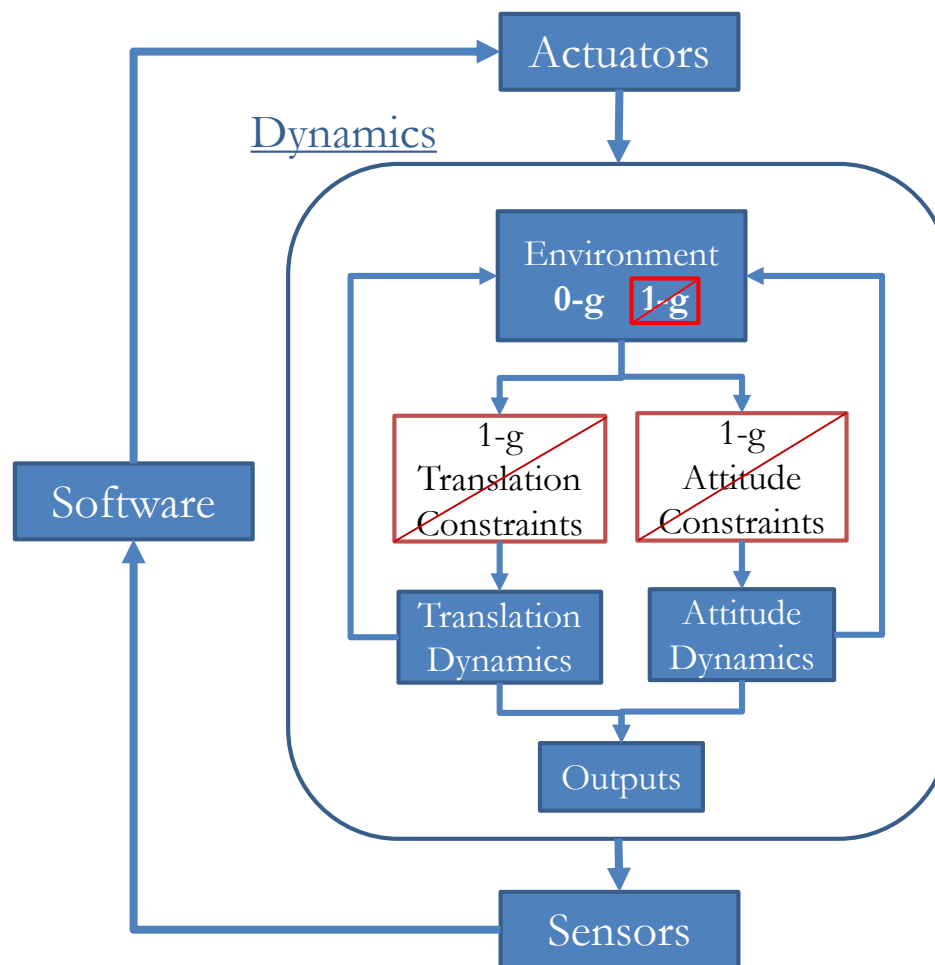
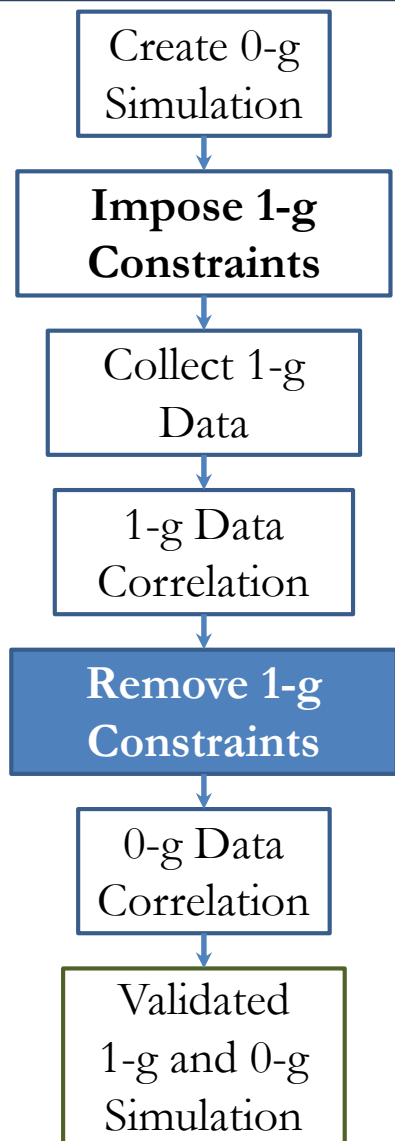


Correlation of 1-g environmental models with 1-g test data enables validation of Chaser hardware and software



# 0-g Simulation Validation with 1-g Testbeds:

## Remove 1-g Constraints

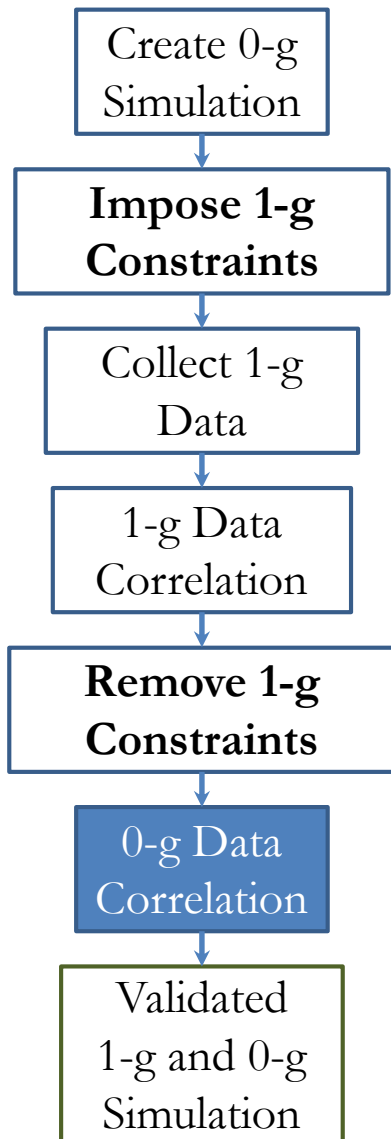


Removing 1-g constraints enables validated models of Chaser hardware and software to be simulated in 0-g



# 0-g Simulation Validation with 1-g Testbeds:

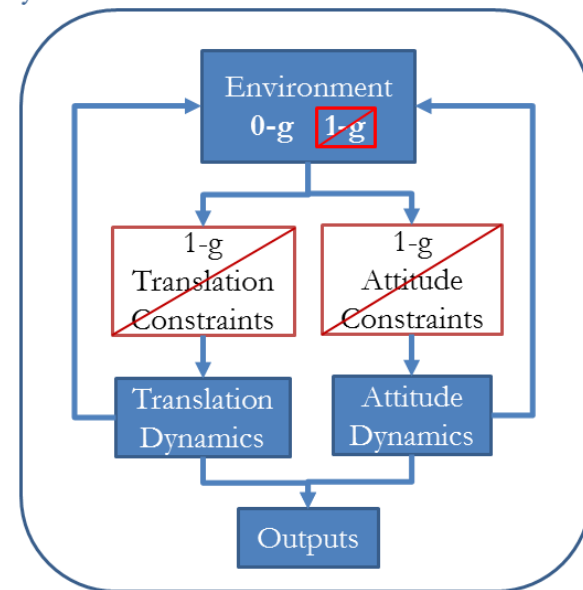
## 0-g Model-Data Correlation



### SSDT Flight Environmental Models

- Disturbance Forces
  - Aerodynamic drag
  - Solar radiation pressure
- Disturbance Torques
  - Aerodynamic drag
  - Solar radiation pressure
  - Gravity gradient
  - Magnetic field

#### Dynamics



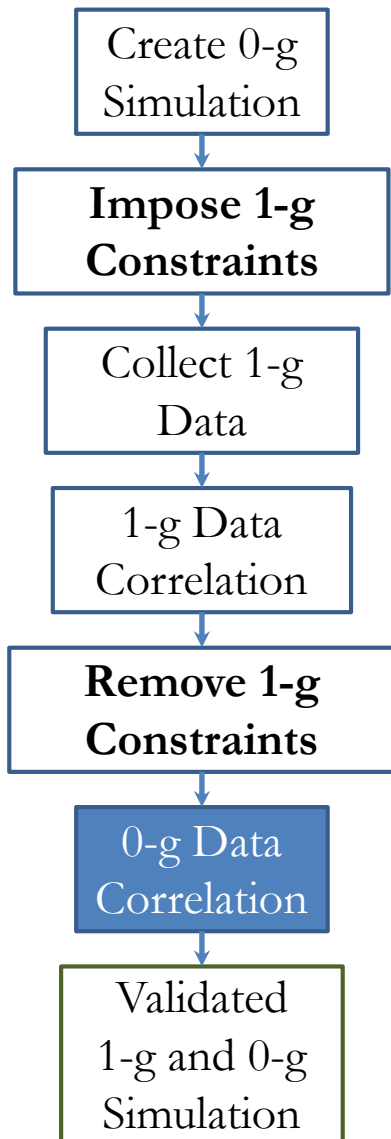
Correlate environmental models with available on-orbit data



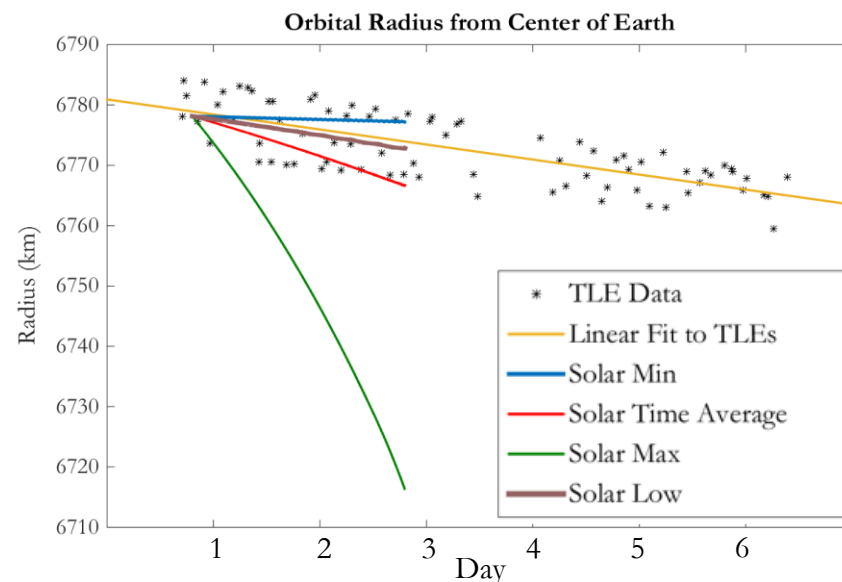
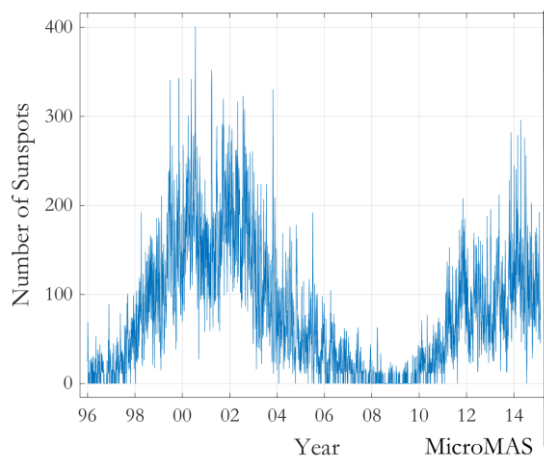
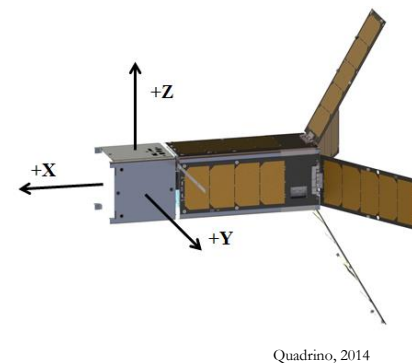
# 0-g Simulation Validation with 1-g Testbeds: NASA



## 0-g Model-Data Correlation



- Lower solar activity leads to less dense atmosphere and slower orbit decay rate
- Tuned simulation atmospheric model approximates TLE data



Correlate environmental models with available on-orbit data



# 0-g Simulation Validation with 1-g Testbeds:

## 0-g Model-Data Correlation

Create 0-g  
Simulation

Impose 1-g  
Constraints

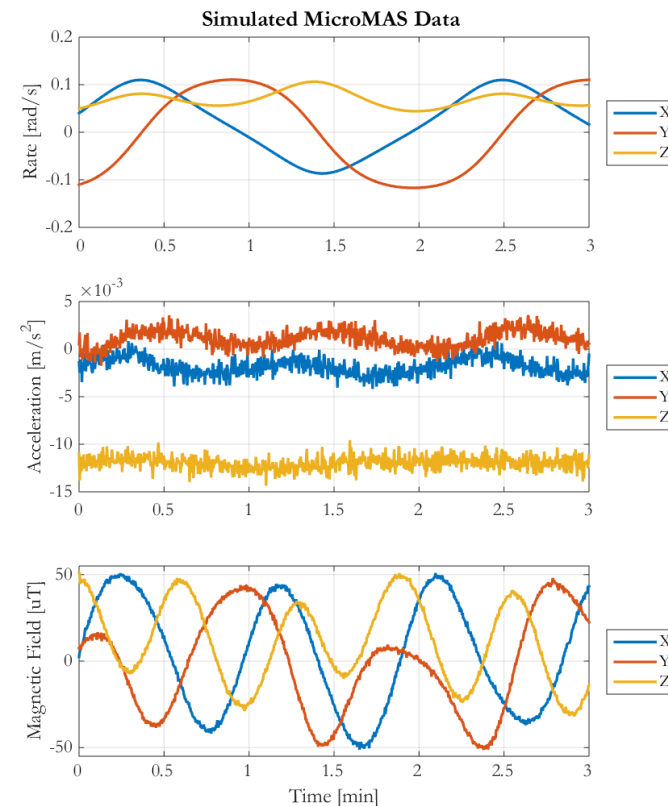
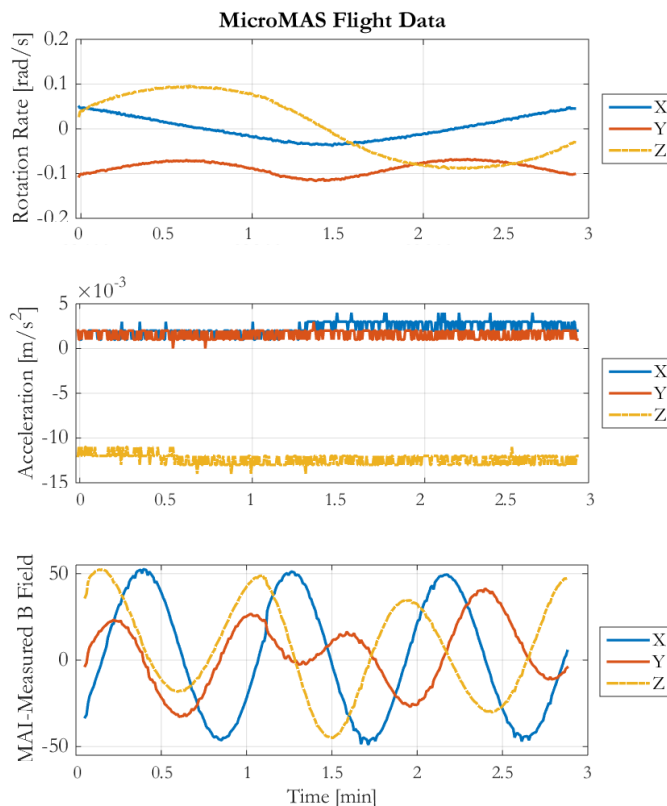
Collect 1-g  
Data

1-g Data  
Correlation

Remove 1-g  
Constraints

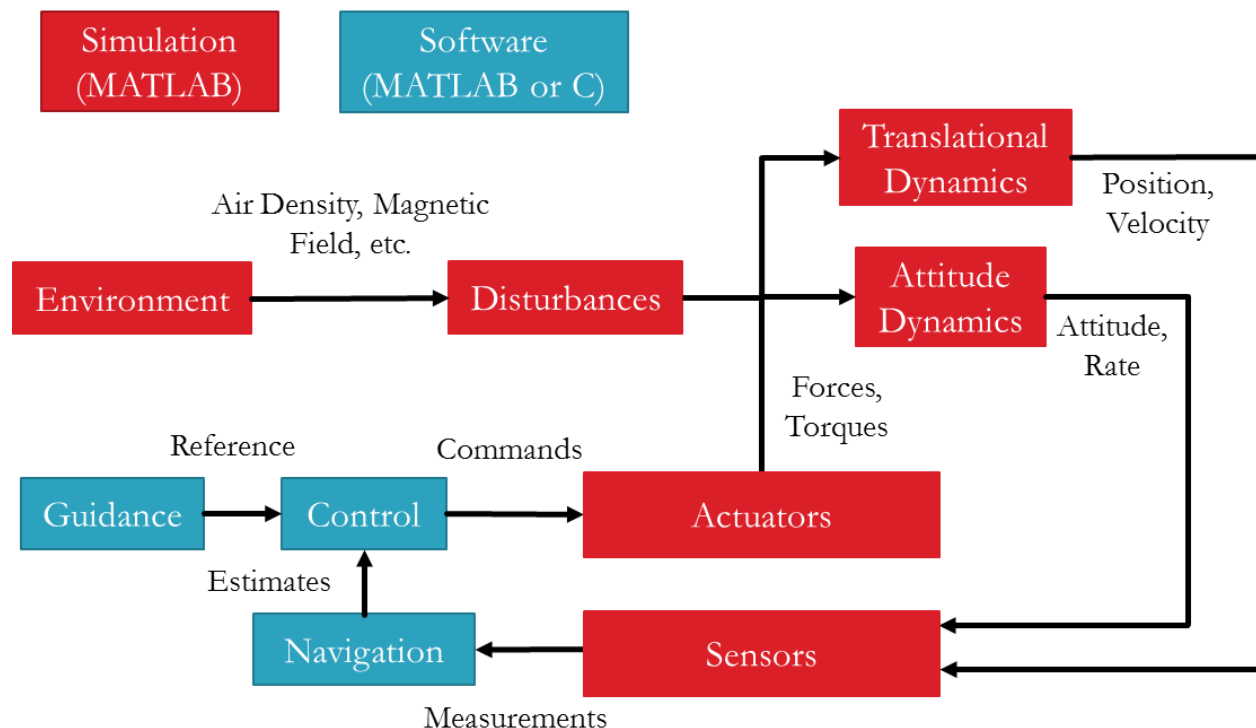
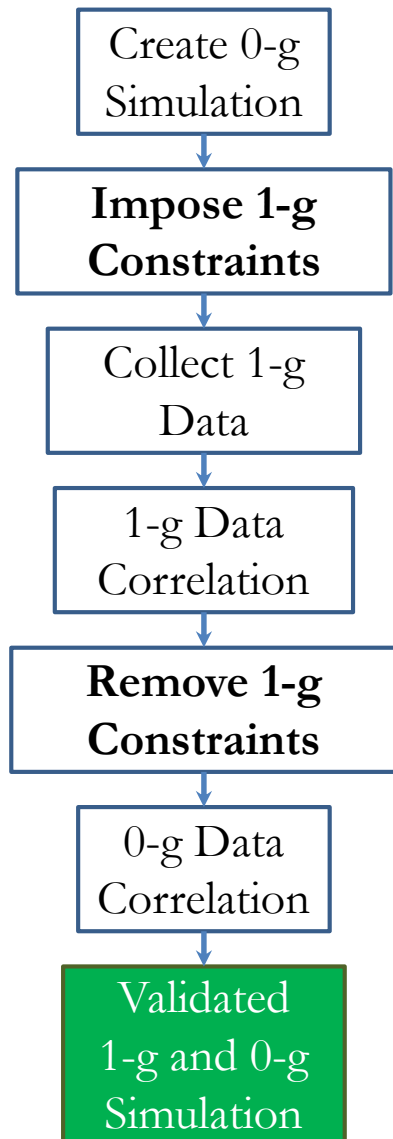
0-g Data  
Correlation

Validated  
1-g and 0-g  
Simulation



Validated models of flight environment and ground-validated Chaser hardware and software models

# Validated 0-g Simulation through Ground Hardware Testing



Thesis Contribution: Improved method of validating a 0-g simulation using constrained 1-g hardware testing